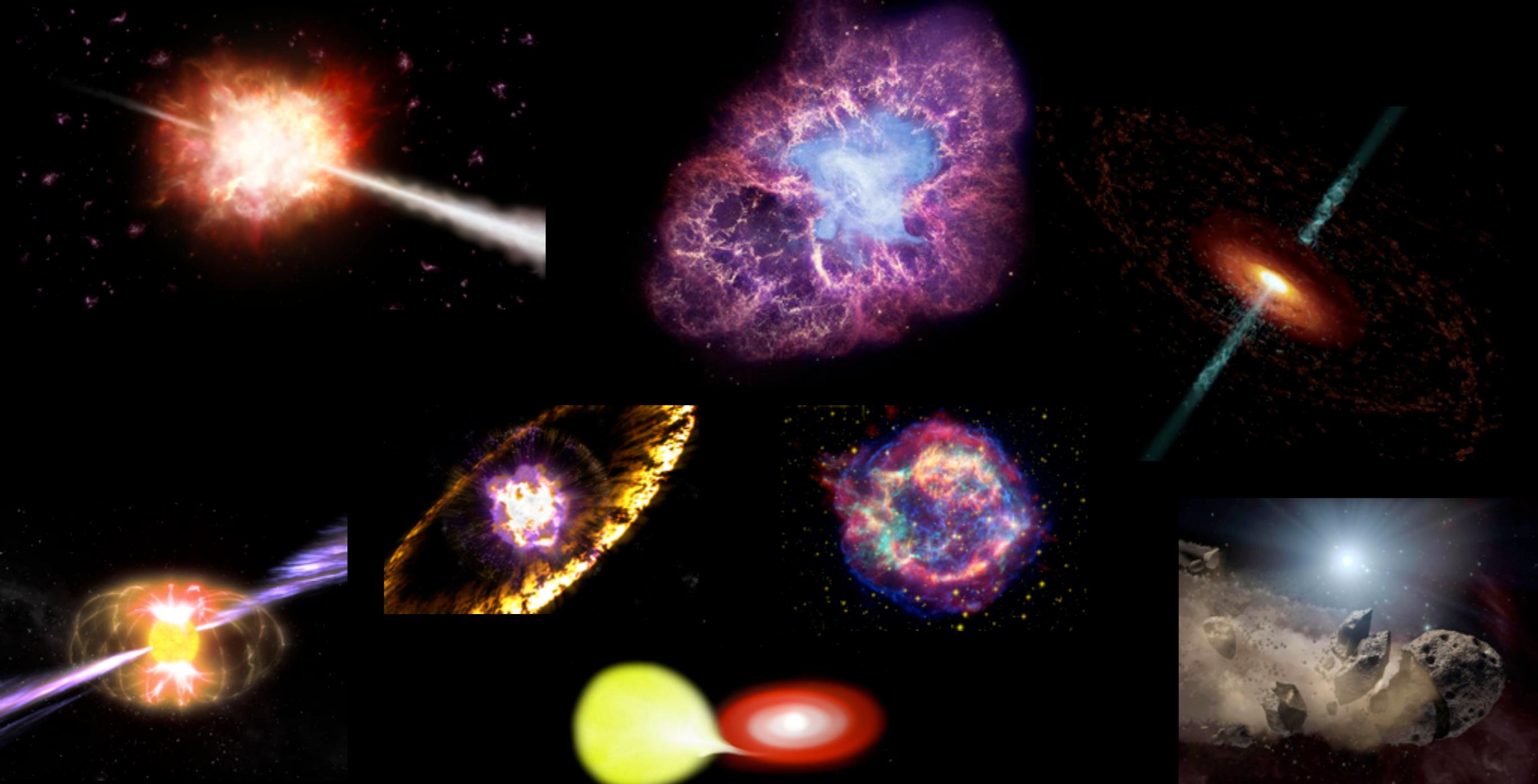


# Observing the transient sky with ultrahigh energy multi-messengers

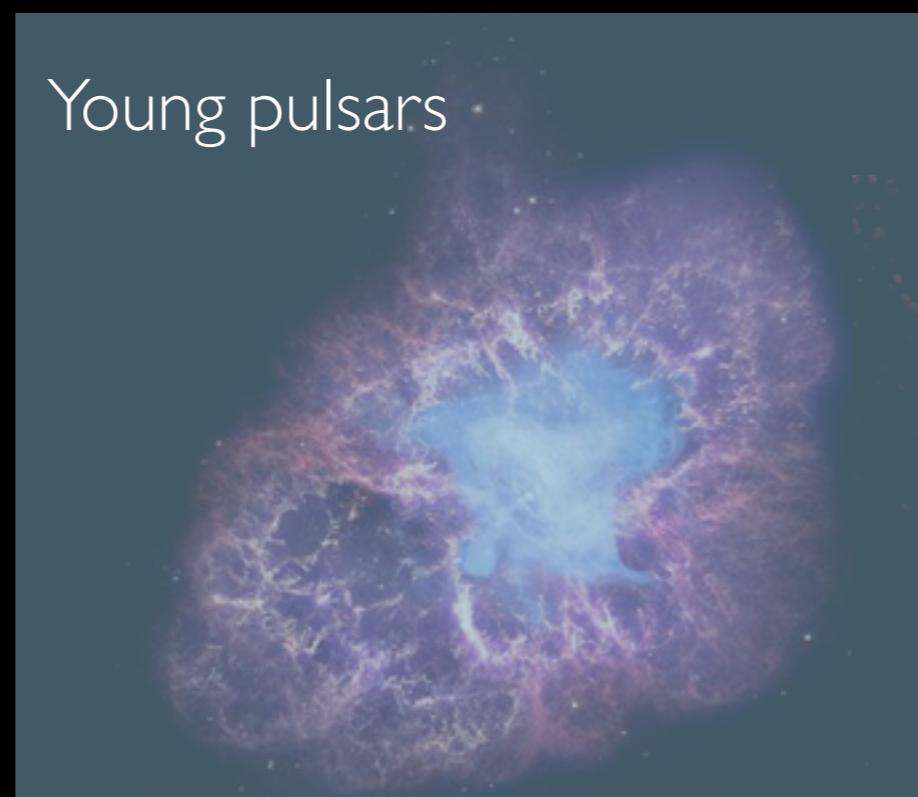


# The Transient Sky at High Energies

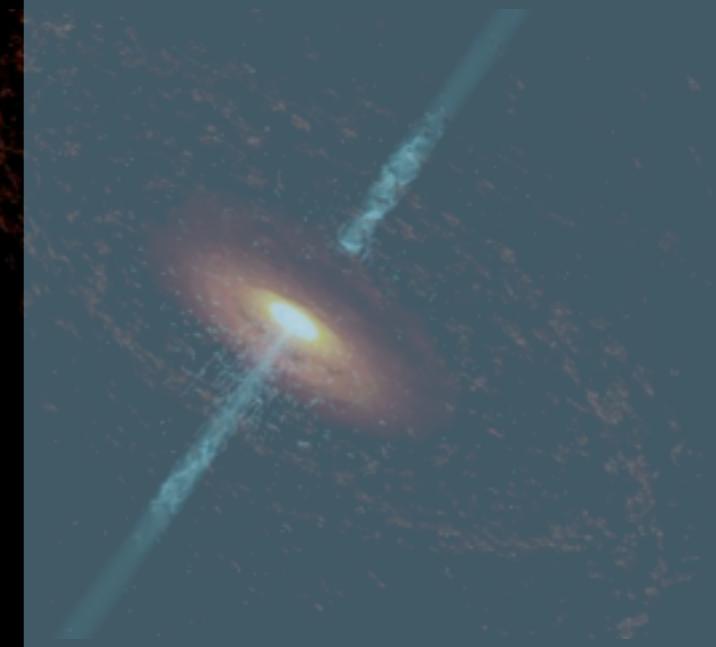
Gamma Ray Bursts (GRBs)  
prompt + afterglow + flares



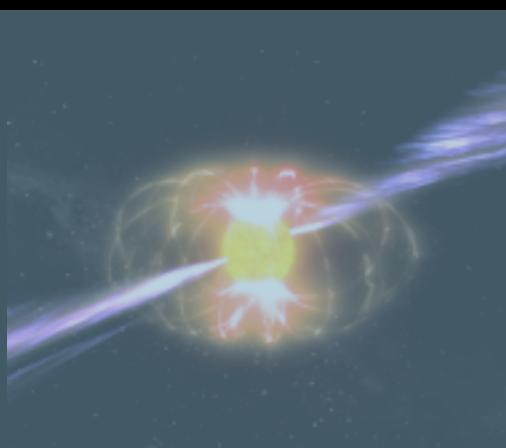
Young pulsars



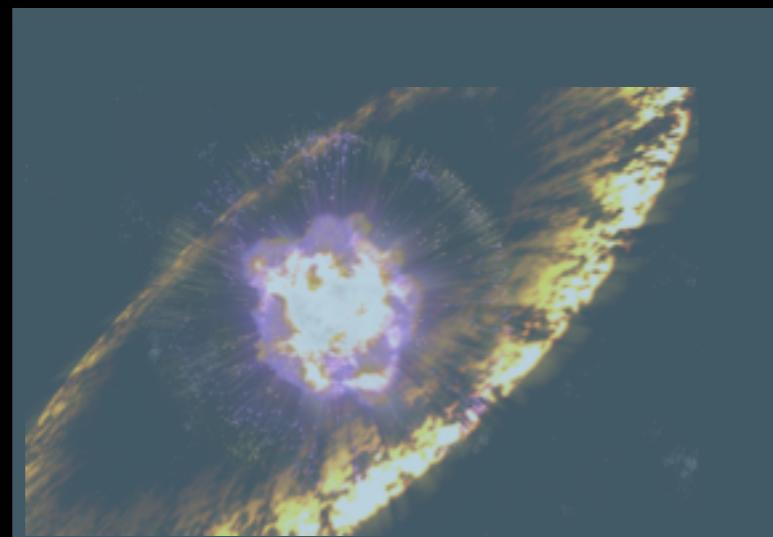
AGN/Blazars  
flares, time-variations



Magnetars  
(AXP/SGR)



Superluminous  
Supernovae



Core-collapse  
Supernovae



Novae

Millisecond pulsars  
and their companions

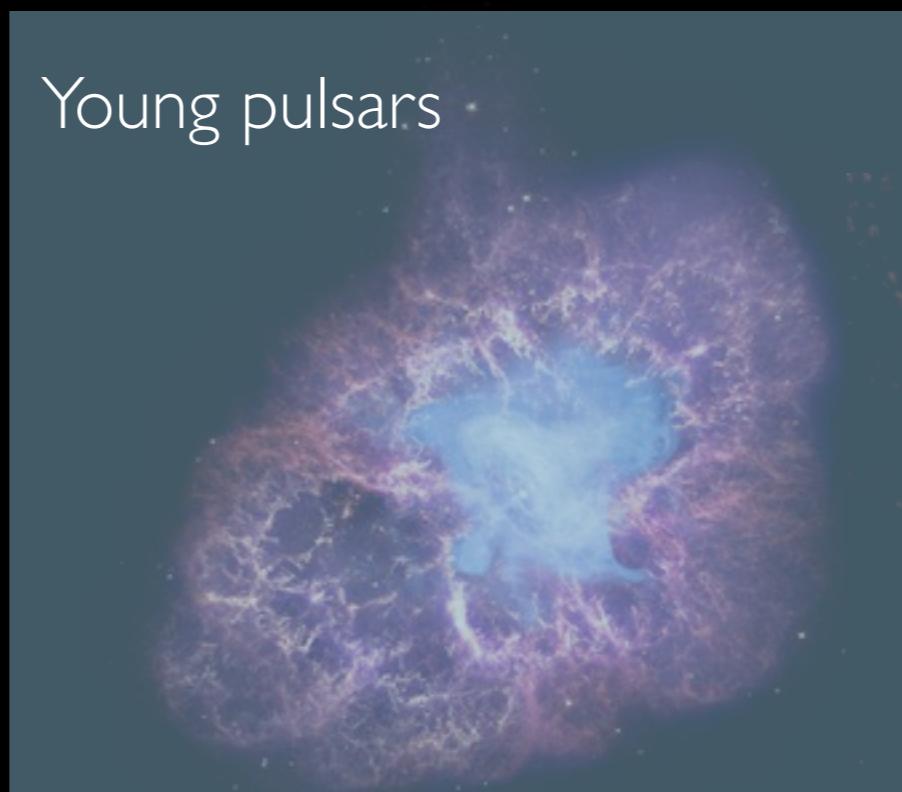


# The Transient Sky at High Energies observed with photons: from radio to gamma-rays

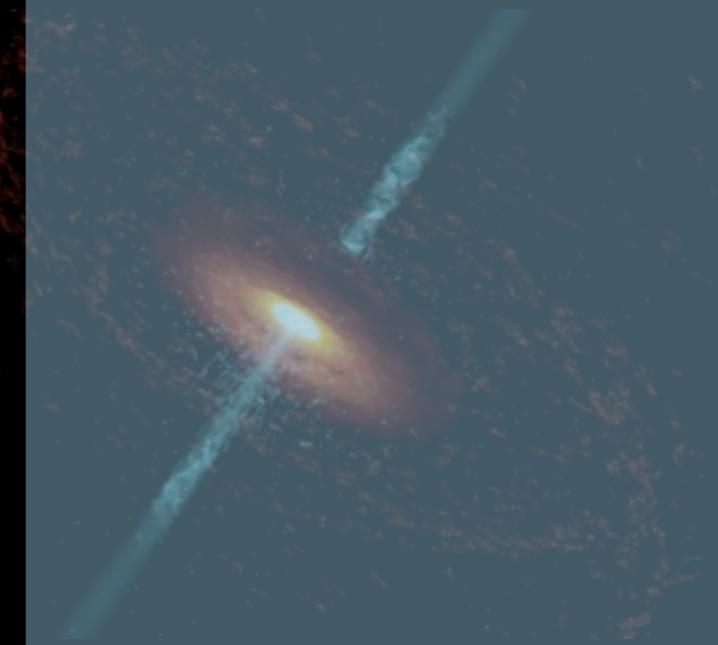
Gamma Ray Bursts (GRBs)  
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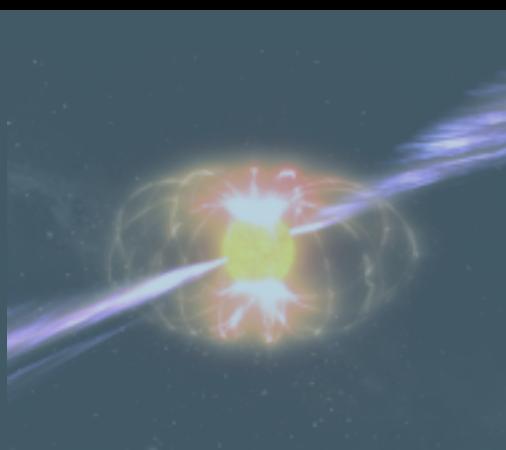
Young pulsars



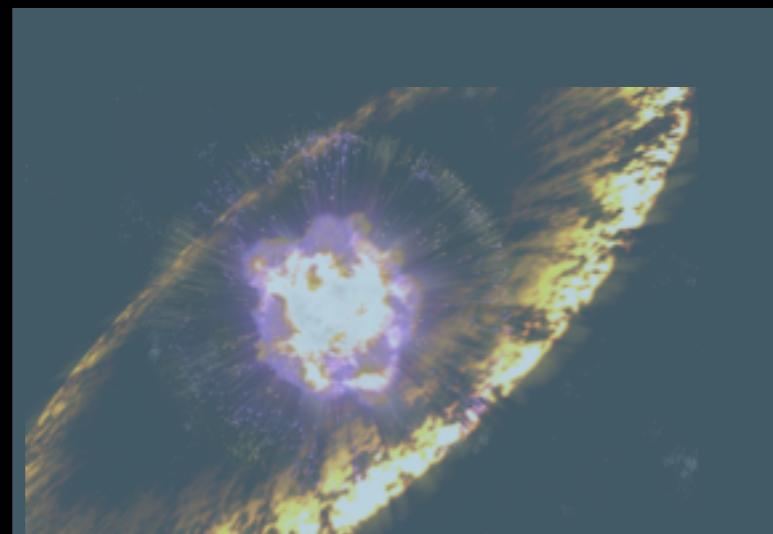
AGN/Blazars  
flares, time-variations



Magnetars  
(AXP/SGR)



Superluminous  
Supernovae

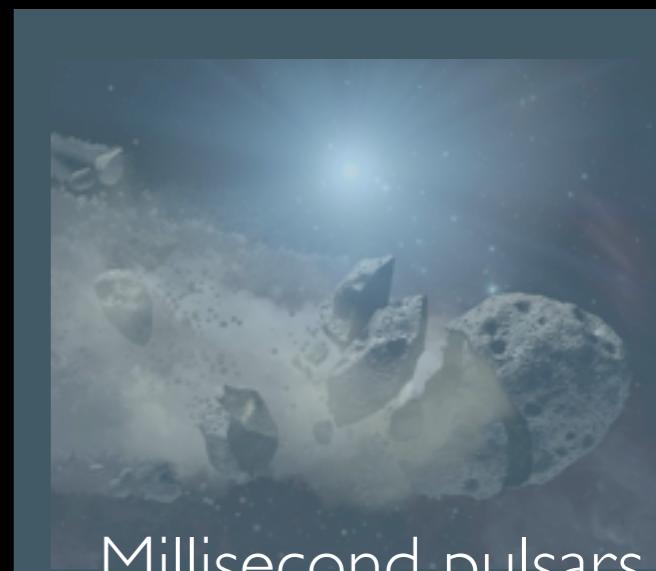


Core-collapse  
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# The Transient Sky at High Energies

Gamma Ray Bursts (GRBs)  
prompt  
+ afterglow  
+ flares



Kohta Murase  
(Penn State U.)

Young pulsars



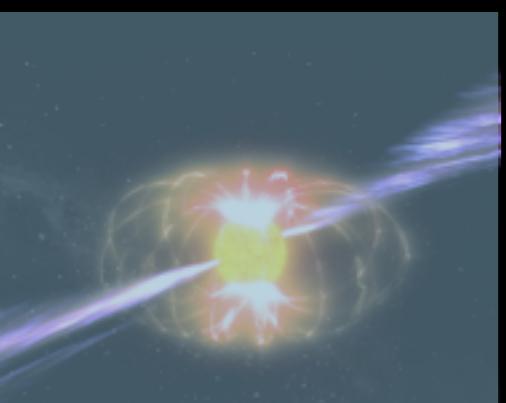
Ke Fang (U. Maryland)

AGN/Blazars  
flares, time-variations



Foteini Oikonomou  
(Penn State U.)

Magnetars  
(AXP/SGR)

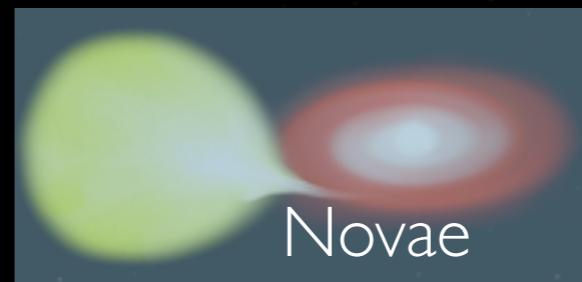


Superluminous  
Supernovae



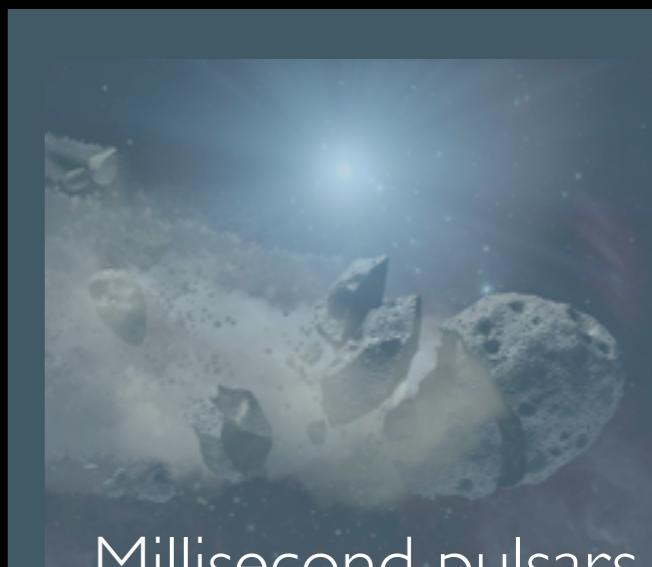
Nicolas Renault-Tinacci  
(IAP)

Core-collapse  
Supernovae



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Millisecond pulsars  
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# Why study the transient sky with UHE messengers?



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Why transients are likely sources of UHE messengers

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cosmic rays

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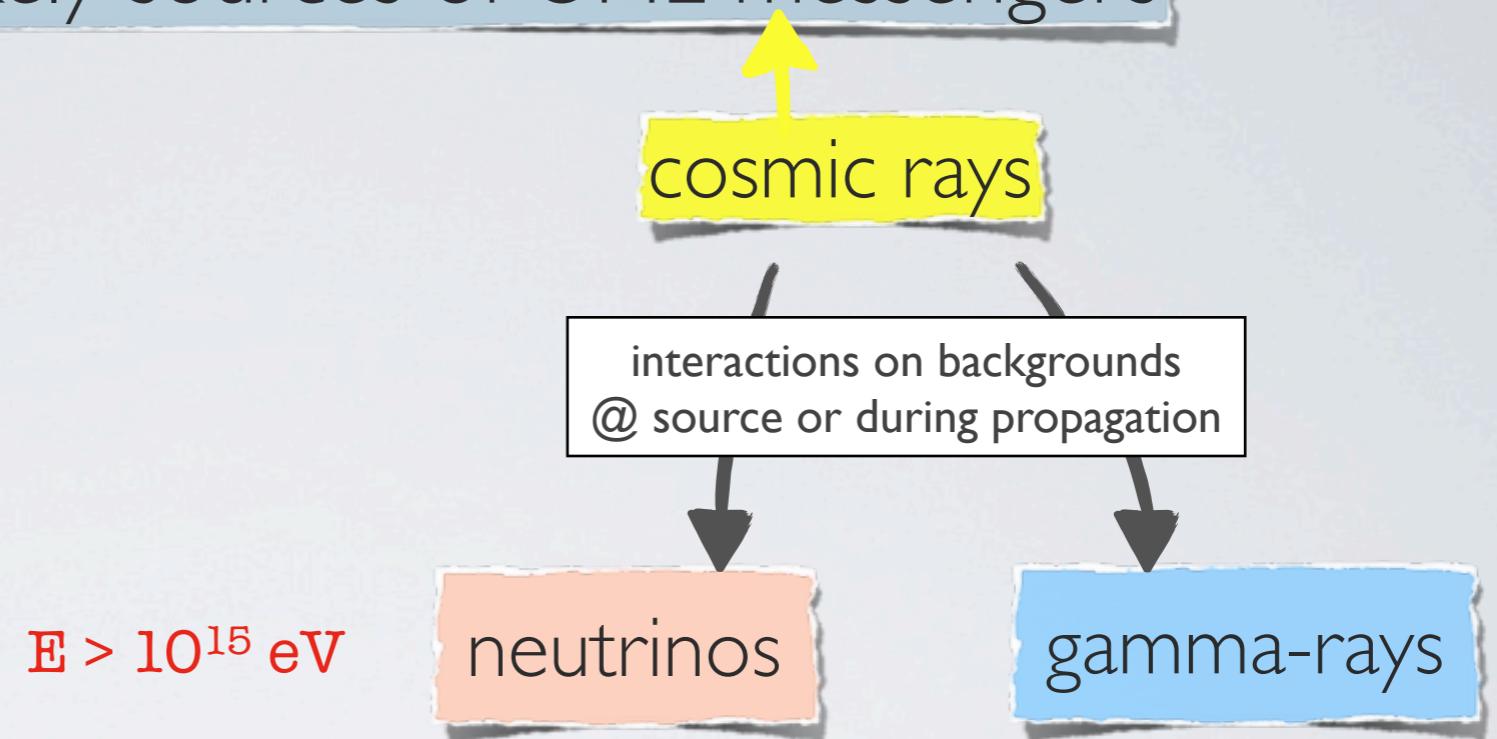
interactions on backgrounds  
@ source or during propagation

neutrinos

gamma-rays

Why study the transient sky with UHE messengers?

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$E > 10^{15}$  eV

Why study the transient sky with UHE messengers?

Why transients are likely sources of UHE messengers

$E_{\text{CR}} > 10^{17} \text{ eV}$

5-10% of  $E_{\text{CR}}$

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- ▶ At very high energy,  
everything is primarily connected to ultrahigh energy cosmic rays

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- ▶ At very high energy,  
everything is primarily connected to ultrahigh energy cosmic rays
  
- ▶ But cosmic rays are deflected by magnetic fields,  
so combine multi-messenger information

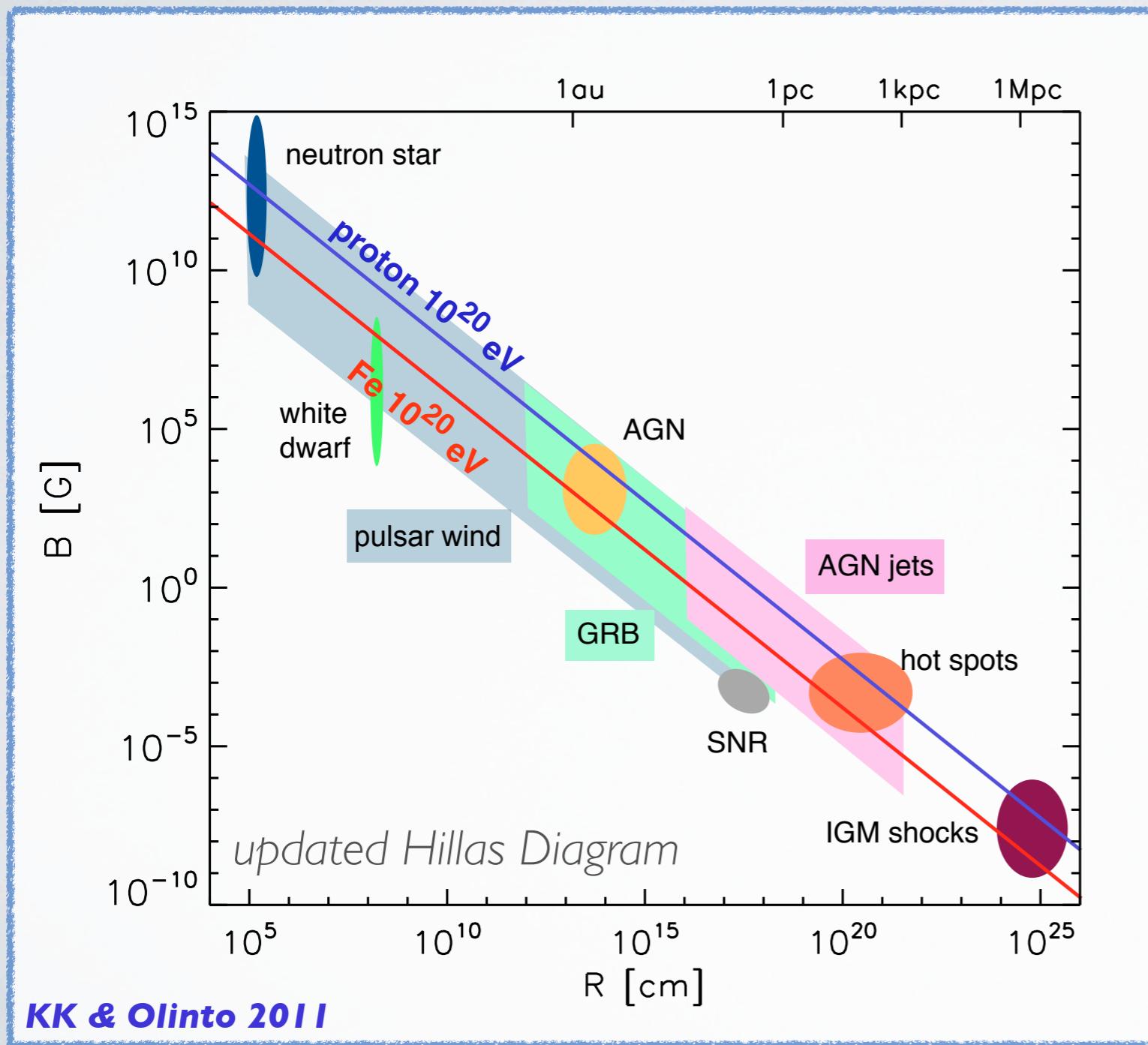
# Selection of UHECR candidate sources

to accelerate, first confine in source:  $r_L \leq R$  size of source

$$E \leq E_{\max} \sim 10^{15} \text{ eV} \times Z \left( \frac{B}{1 \mu\text{G}} \right) \left( \frac{R}{1 \text{ pc}} \right)$$

$$r_L = 1.08 \text{ Mpc } Z^{-1} \left( \frac{E}{10^{18} \text{ eV}} \right) \left( \frac{B}{1 \text{ nG}} \right)^{-1}$$

particle charge	particle energy	source mag. field
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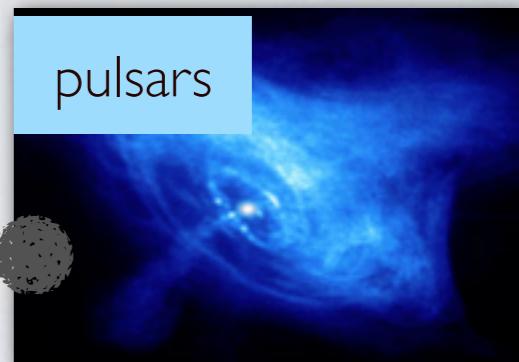
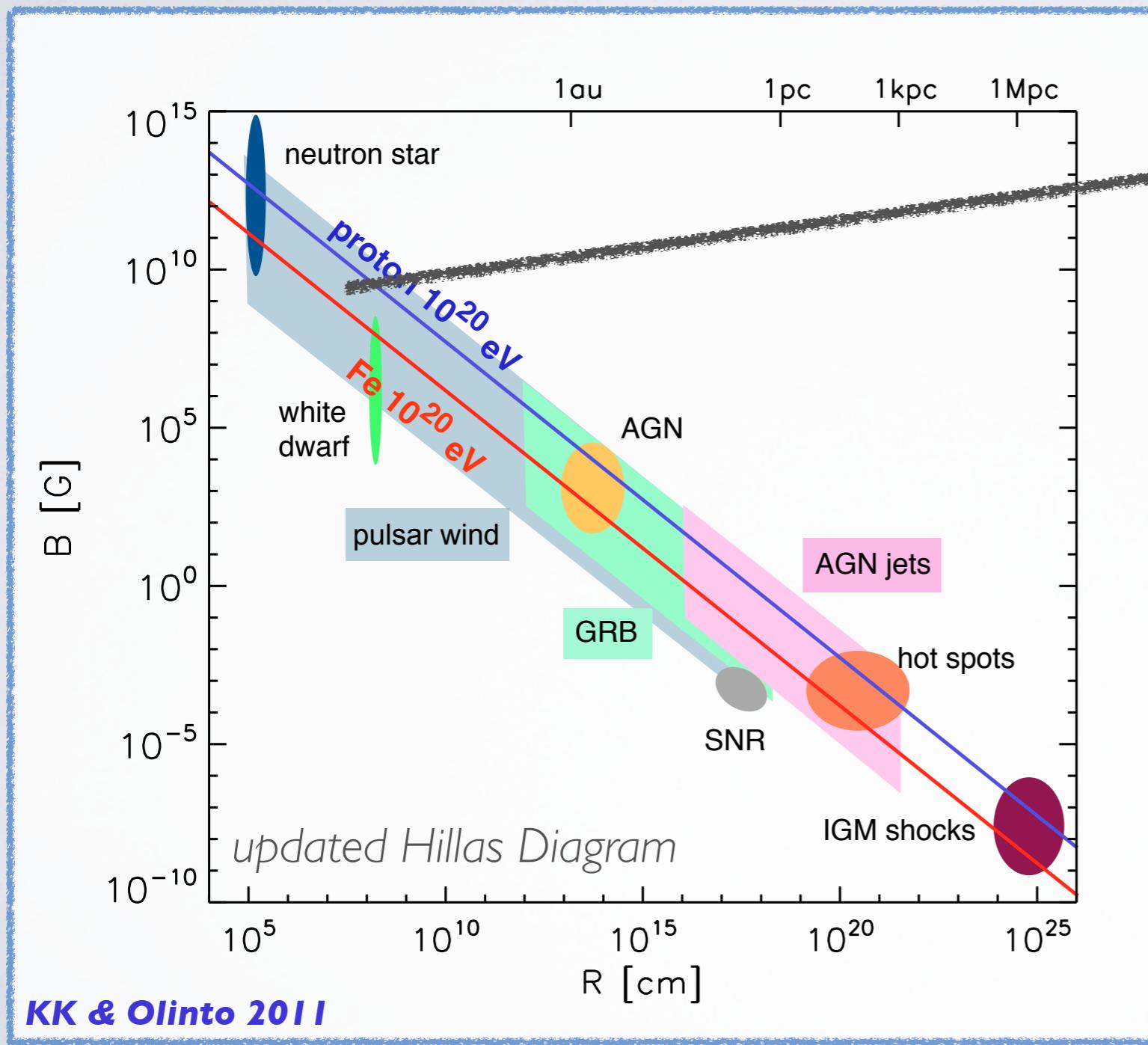
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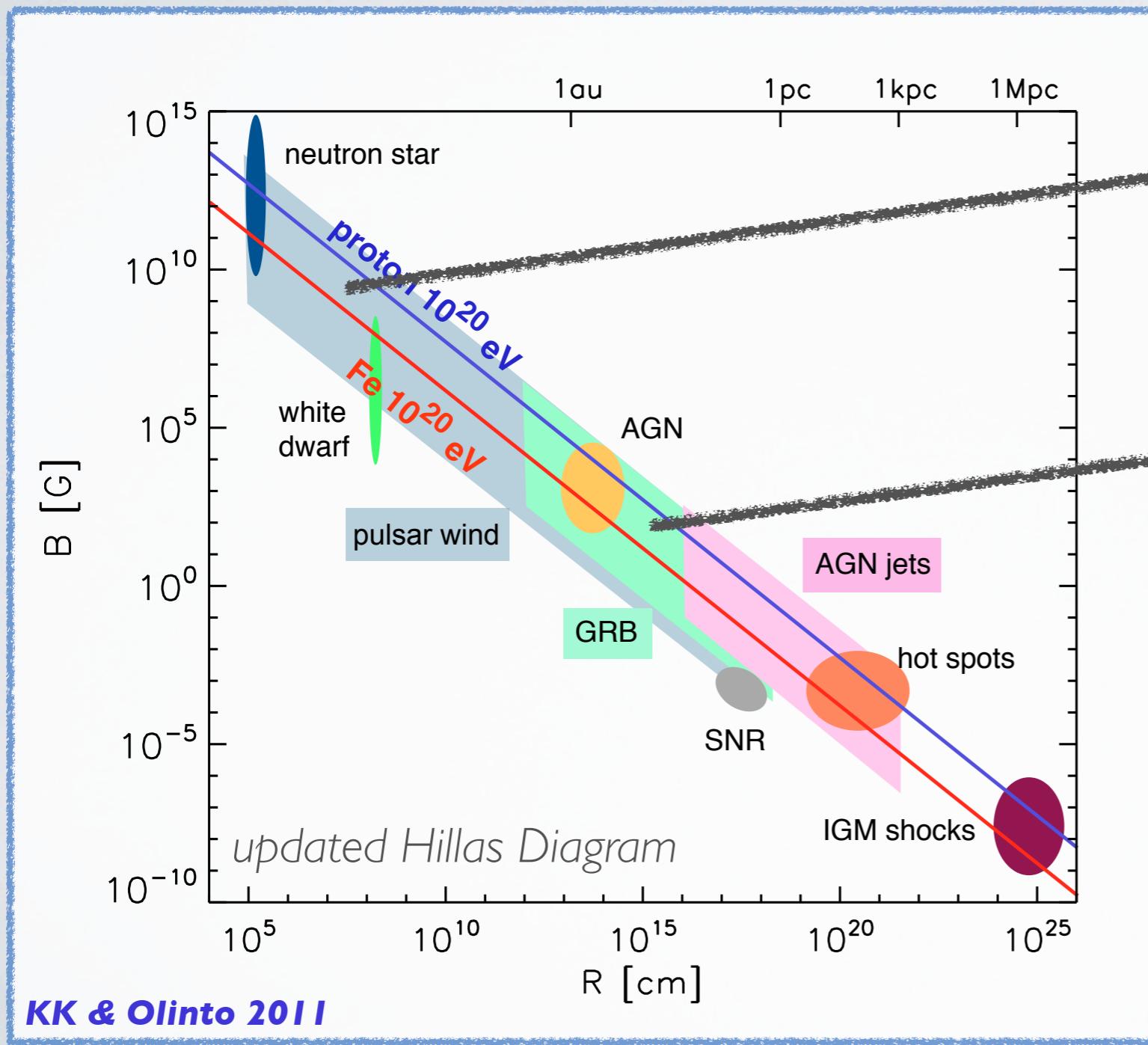
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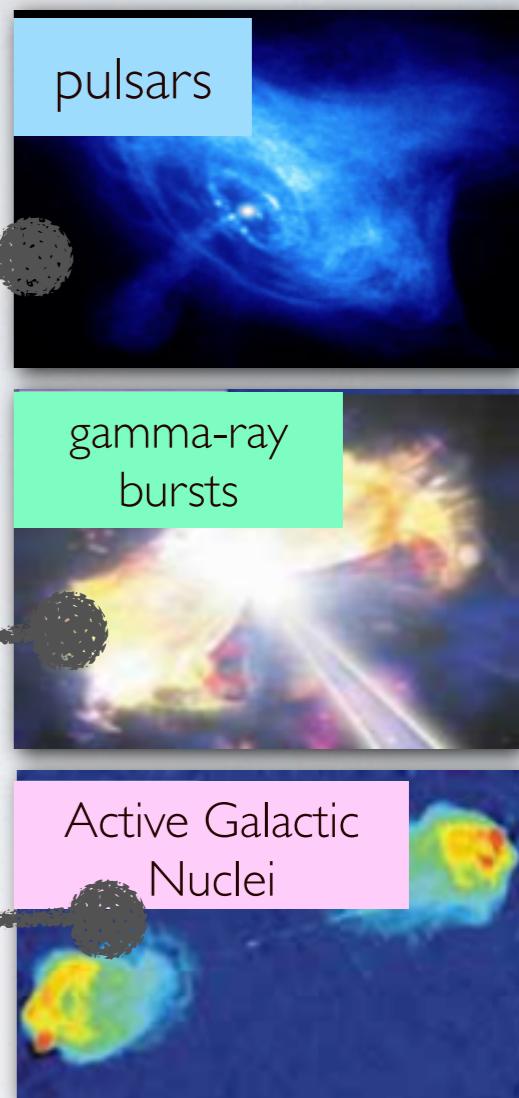
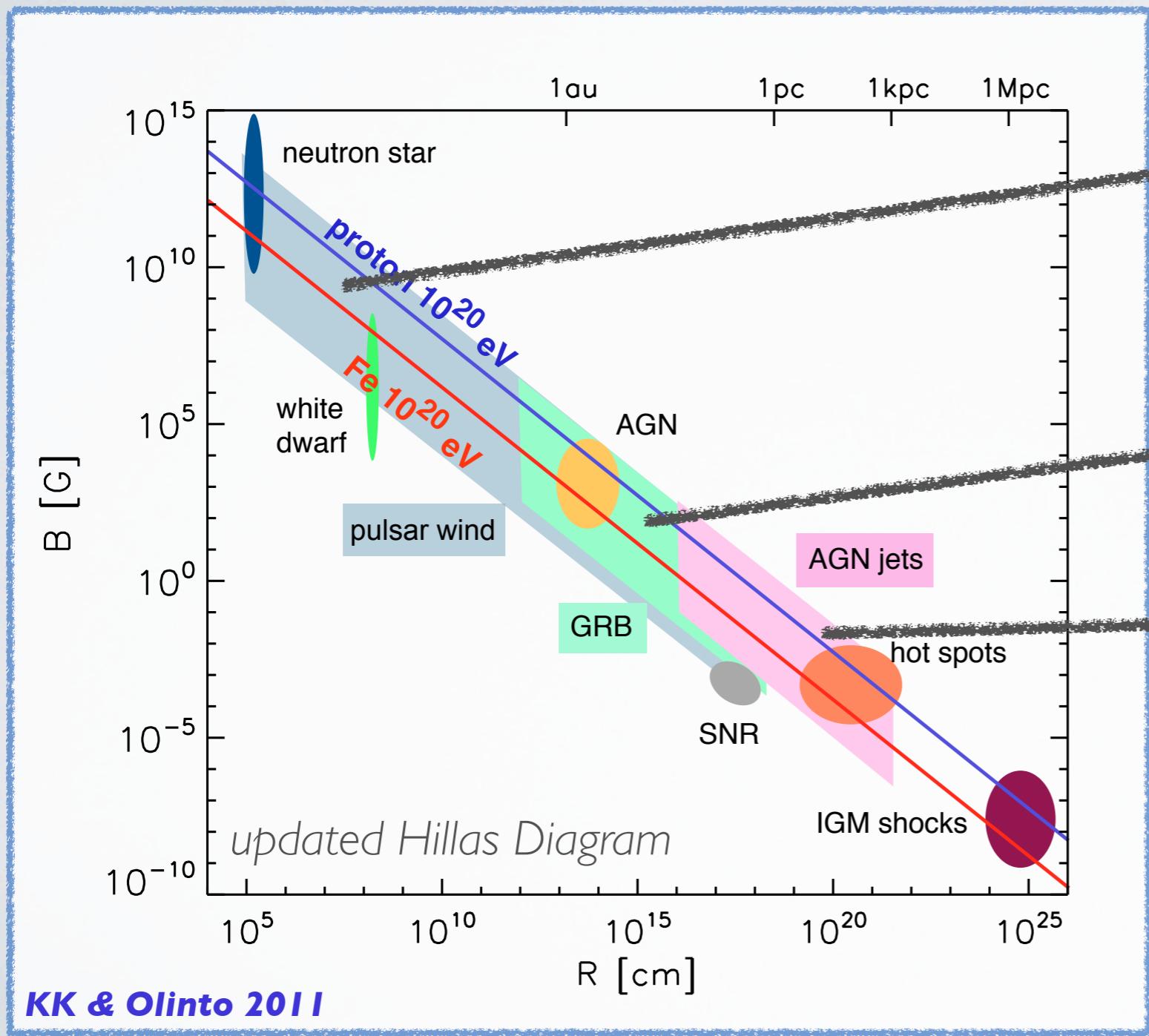
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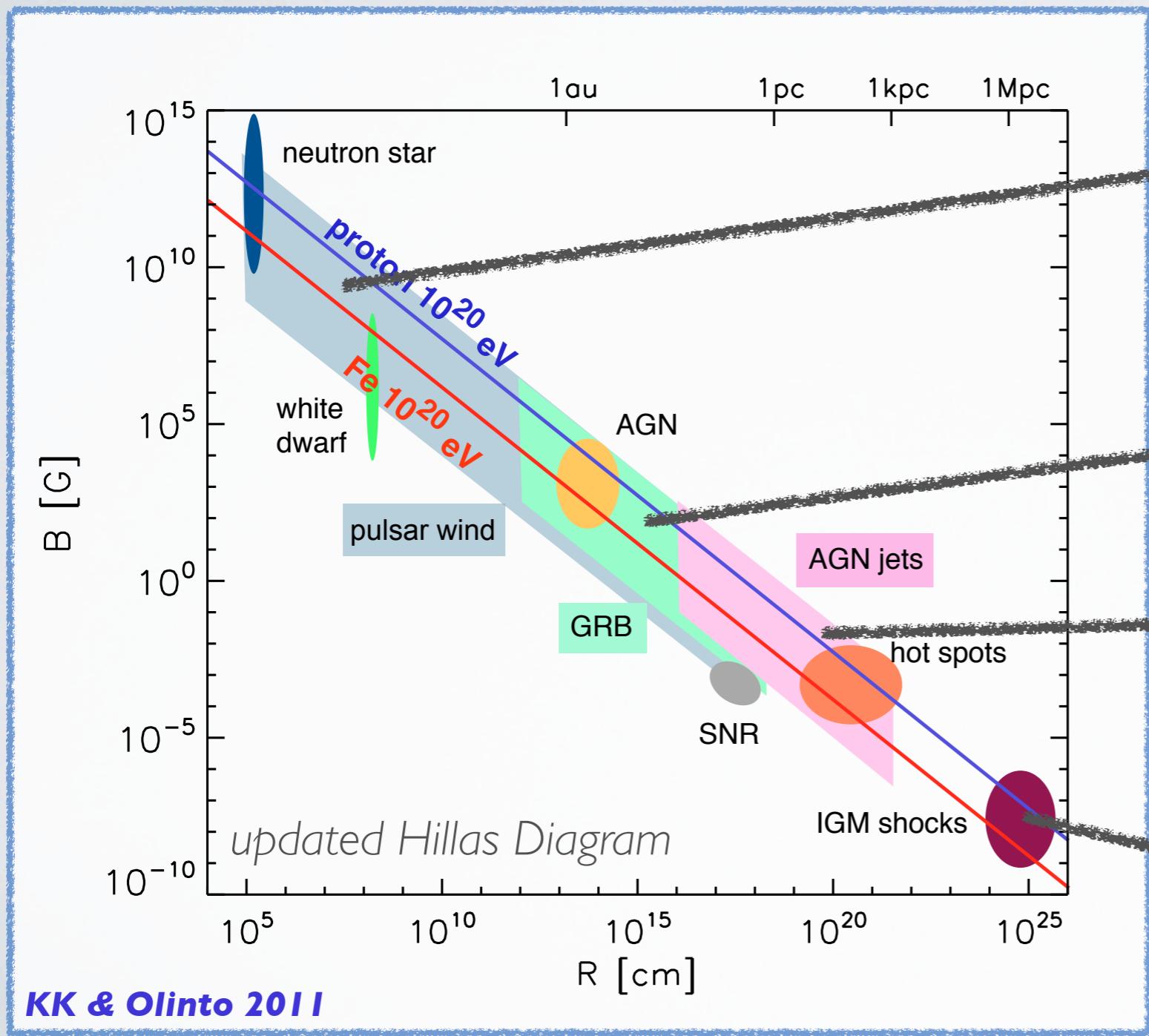
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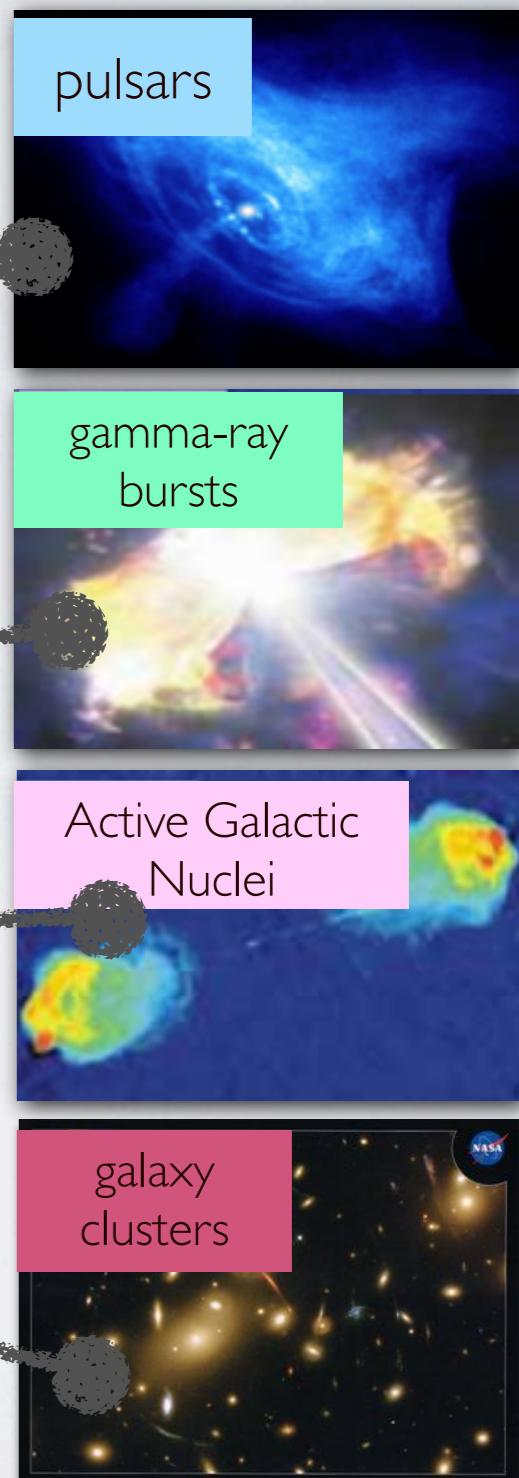
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KK & Olinto 2011



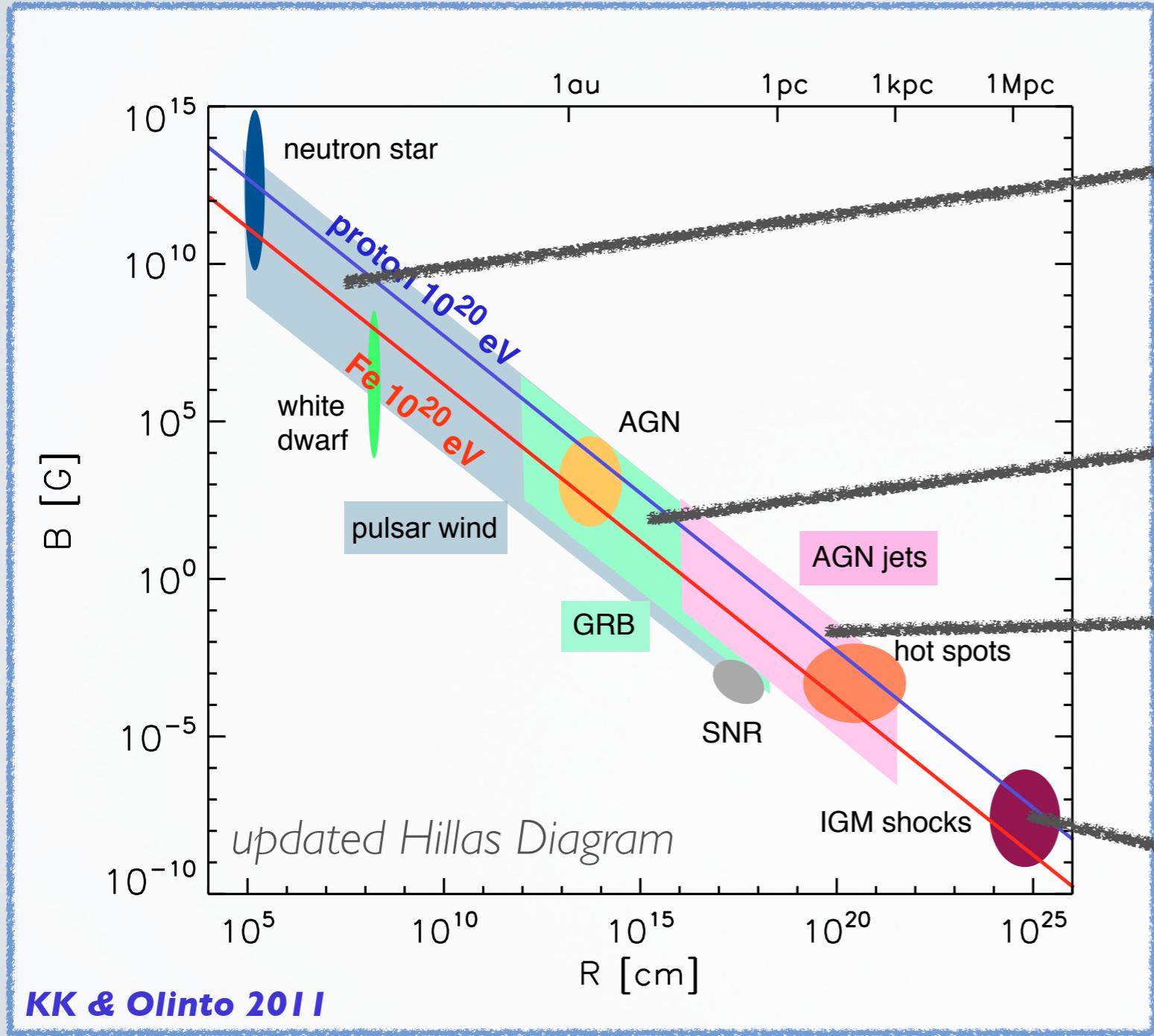
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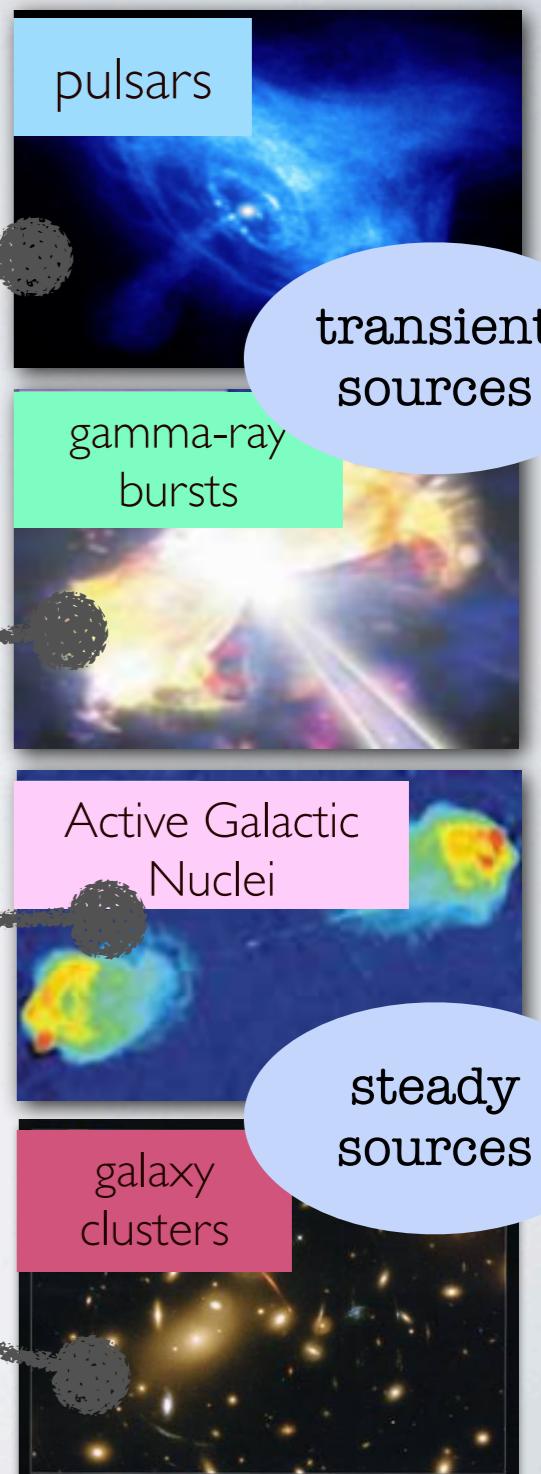
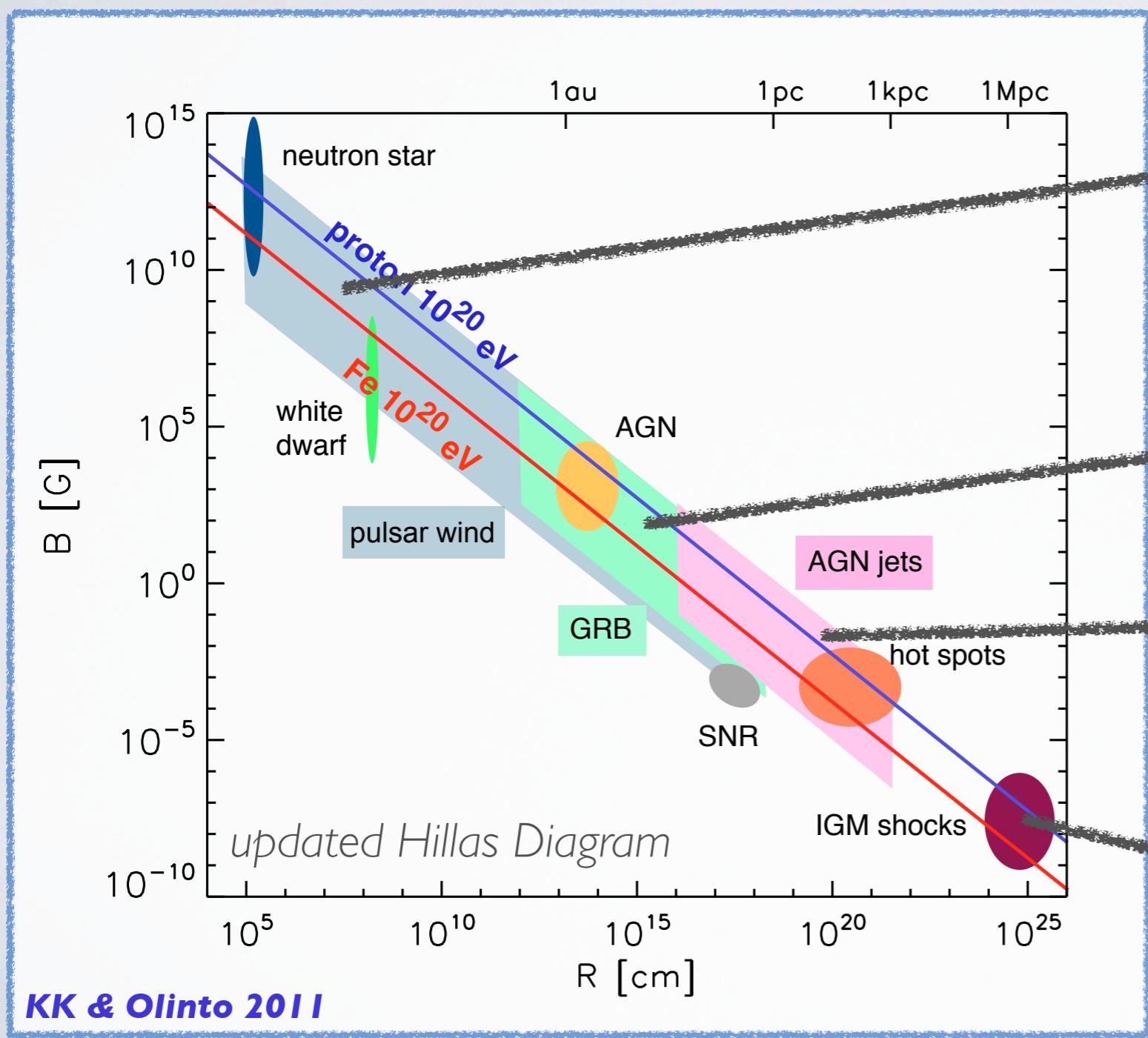
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# A luminosity bound

condition for acceleration

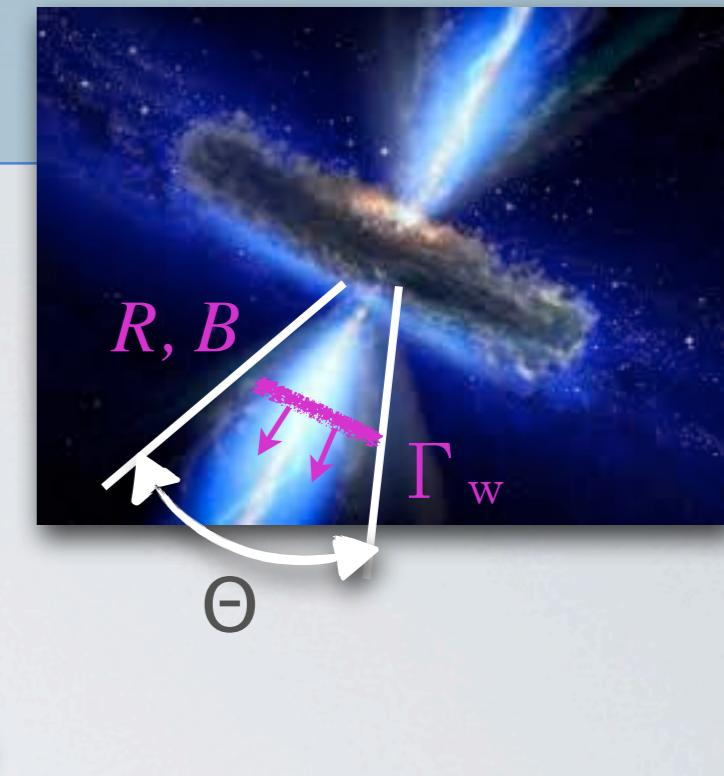
$$t_{\text{acc}} \lesssim t_{\text{dyn}}$$

$$t_{\text{acc}} = \mathcal{A} t_L$$

depends on  
acc. mechanism  
and environment

$\mathcal{A} \gg 1$   
 $\mathcal{A} \sim 1$  at best

$$t_{\text{dyn}} \sim R/\beta_W \Gamma_W c$$



# A luminosity bound

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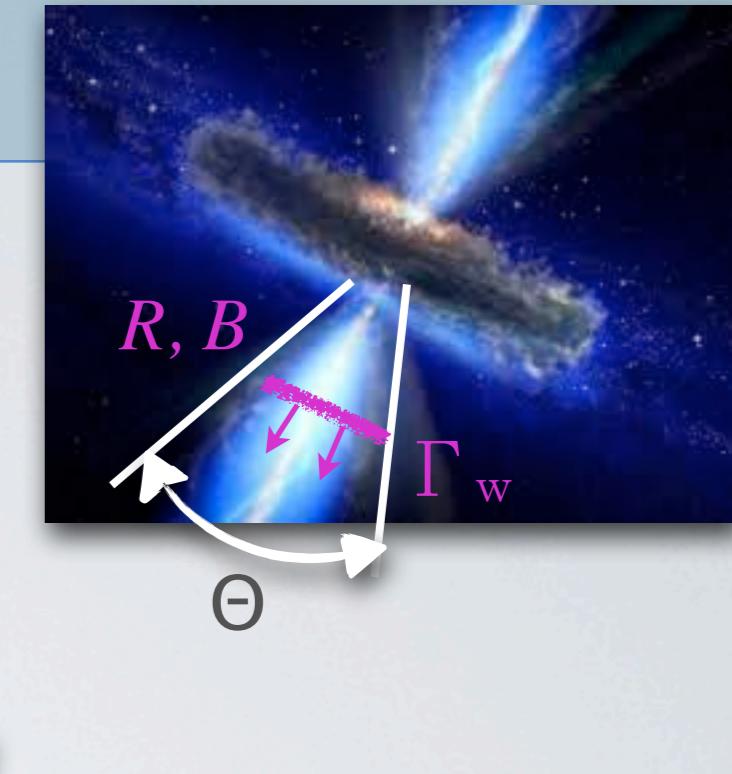
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Larmor time

$$t_{\text{dyn}} \sim R/\beta_W \Gamma_W c$$



outflow magnetic luminosity

$$\begin{aligned} L_B &\equiv \Gamma_W R^2 B^2 / 2 \\ &> 10^{45} Z^{-2} E_{20}^2 \text{ erg s}^{-1} \end{aligned}$$

lower bound of the bolometric luminosity of source

**Lemoine & Waxman 09**

# A luminosity bound

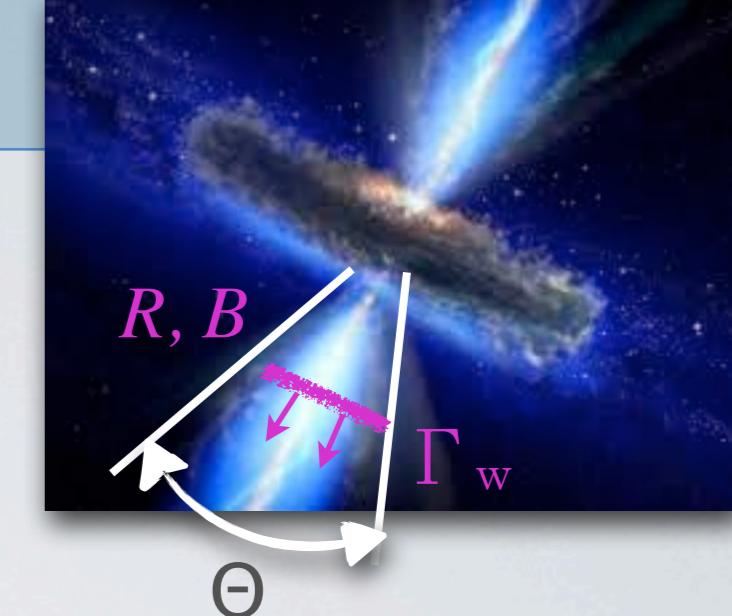
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# A luminosity bound

steady sources



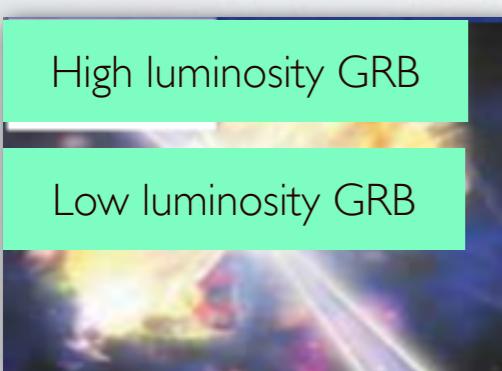
$> 10^{45}$  erg/s



$10^{46-48}$  erg/s



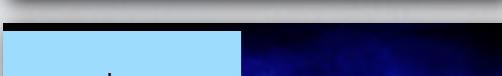
$< 10^{45}$  erg/s



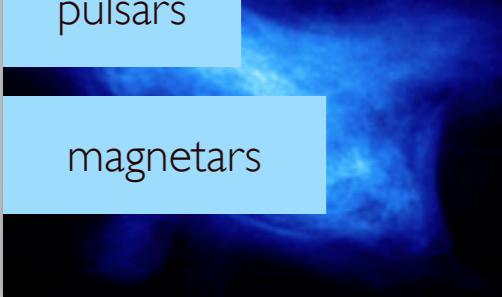
$10^{51-52}$  erg/s



$10^{50-51}$  erg/s



$10^{45-47}$  erg/s



$10^{45-47}$  erg/s

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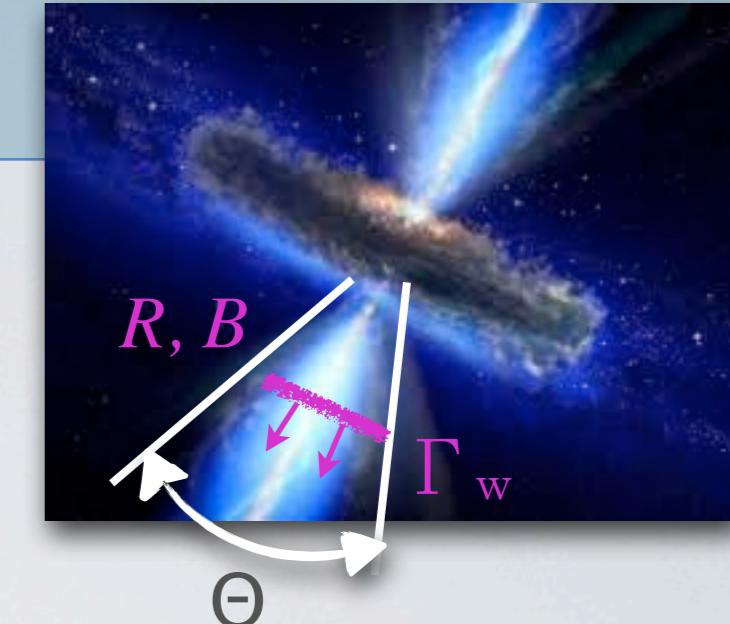
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Larmor time

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outflow magnetic luminosity

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$$> 10^{45} Z^{-2} E_{20}^2 \text{ erg s}^{-1}$$

lower bound of the bolometric luminosity of source

**Lemoine & Waxman 09**

# A luminosity bound

steady sources

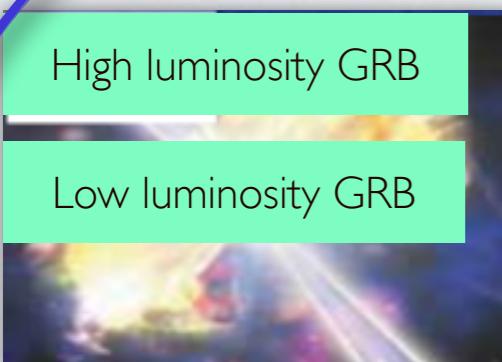


$> 10^{45} \text{ erg/s}$



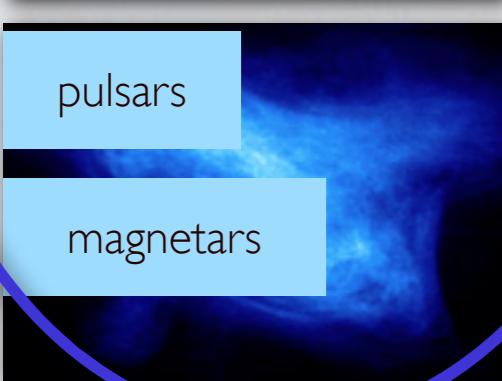
$10^{46-48} \text{ erg/s}$

$< 10^{45} \text{ erg/s}$



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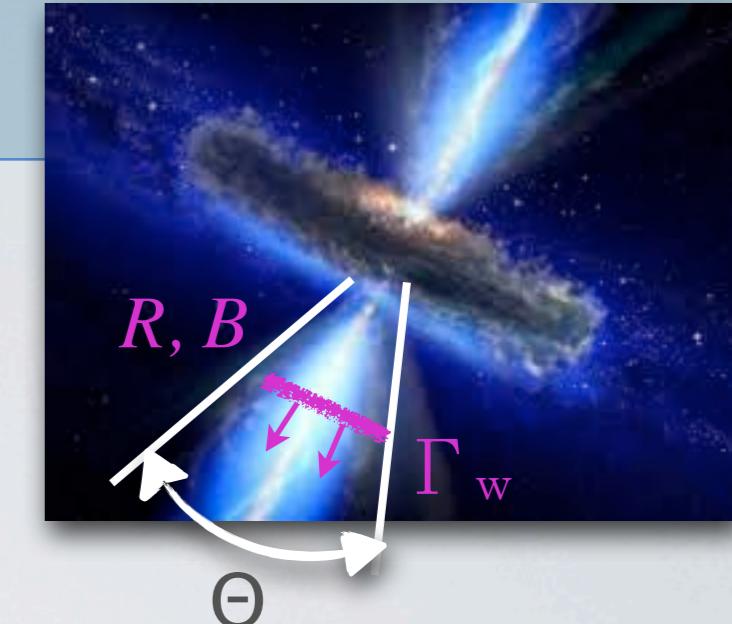
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lower bound of the bolometric luminosity of source

**Lemoine & Waxman 09**



# Total energy budget and number density of sources

steady sources

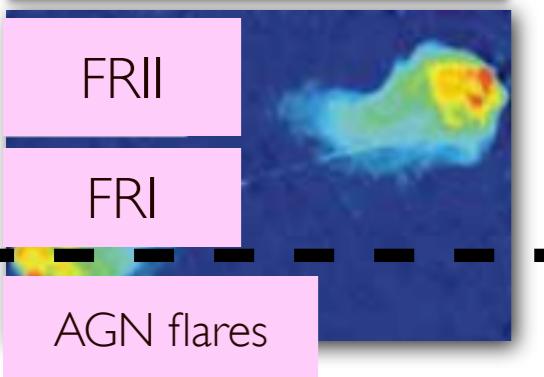


lack of multiplets in the sky (many events from small angular spot)

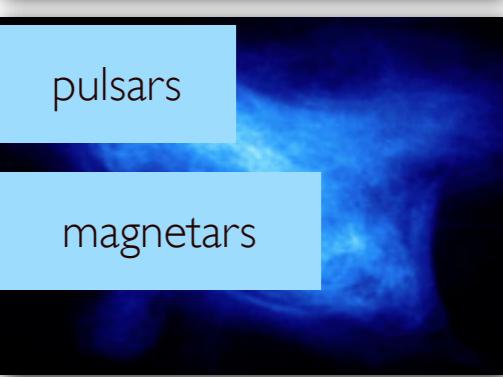
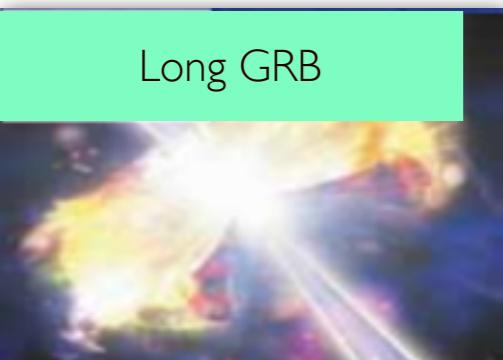
➤ apparent number density of sources:

$$n_0 \gtrsim 10^{-5} \text{ Mpc}^{-3}$$

*Kashti & Waxman 08,  
Takami & Sato 09,  
Abreu et al. 2013*



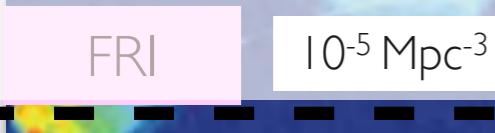
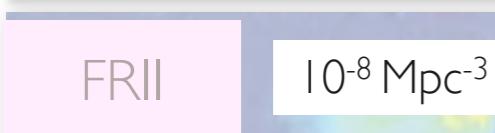
transient sources



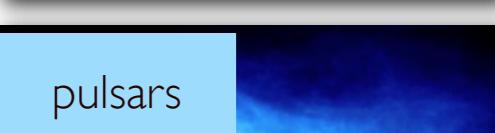
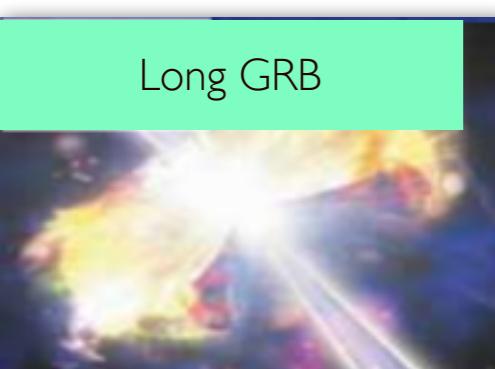
magnetars

# Total energy budget and number density of sources

steady sources



transient sources



lack of multiplets in the sky (many events from small angular spot)

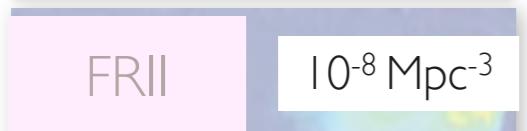
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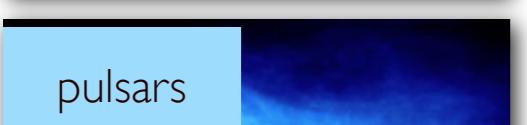
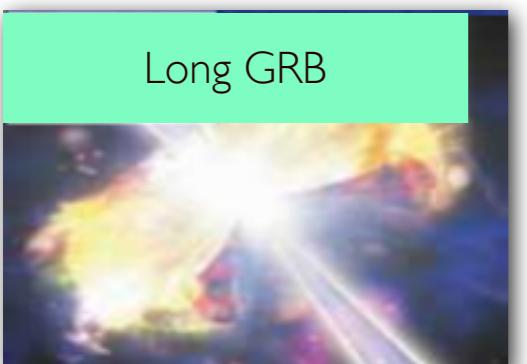
*Kashti & Waxman 08,  
Takami & Sato 09,  
Abreu et al. 2013*

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steady sources



transient sources



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*Kashti & Waxman 08,  
Takami & Sato 09,  
Abreu et al. 2013*

for transient sources: real number density of UHE proton sources

$$\rho_0 \sim n_0 / (\text{CR time spread } \tau_d)$$

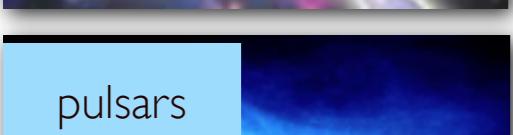
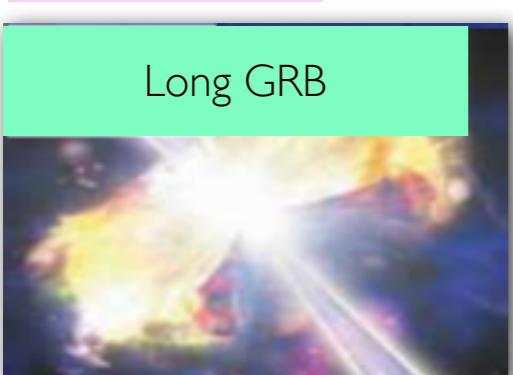
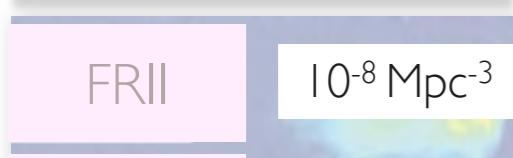
$\tau_d$  depends on extragalactic + Galactic magnetic fields (not known)

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steady sources



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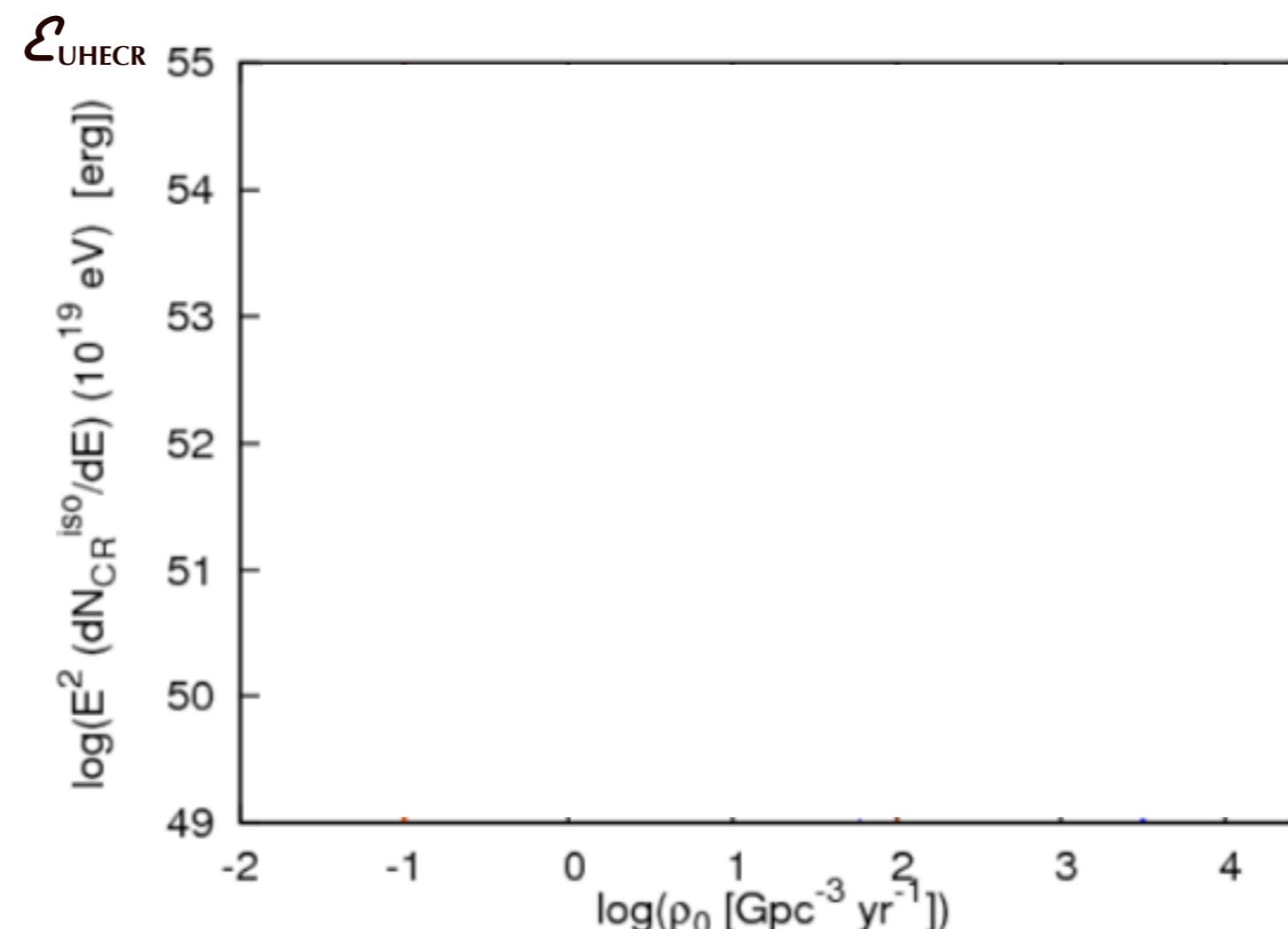
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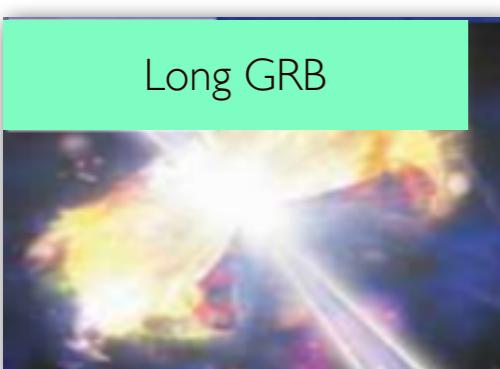
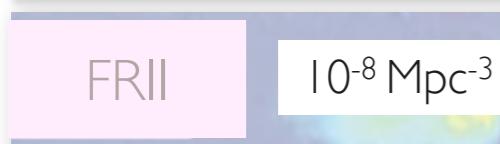
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**Murase & Takami 09**  
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# Total energy budget and number density of sources

steady sources



transient sources

lack of multiplets in the sky (many events from small angular spot)

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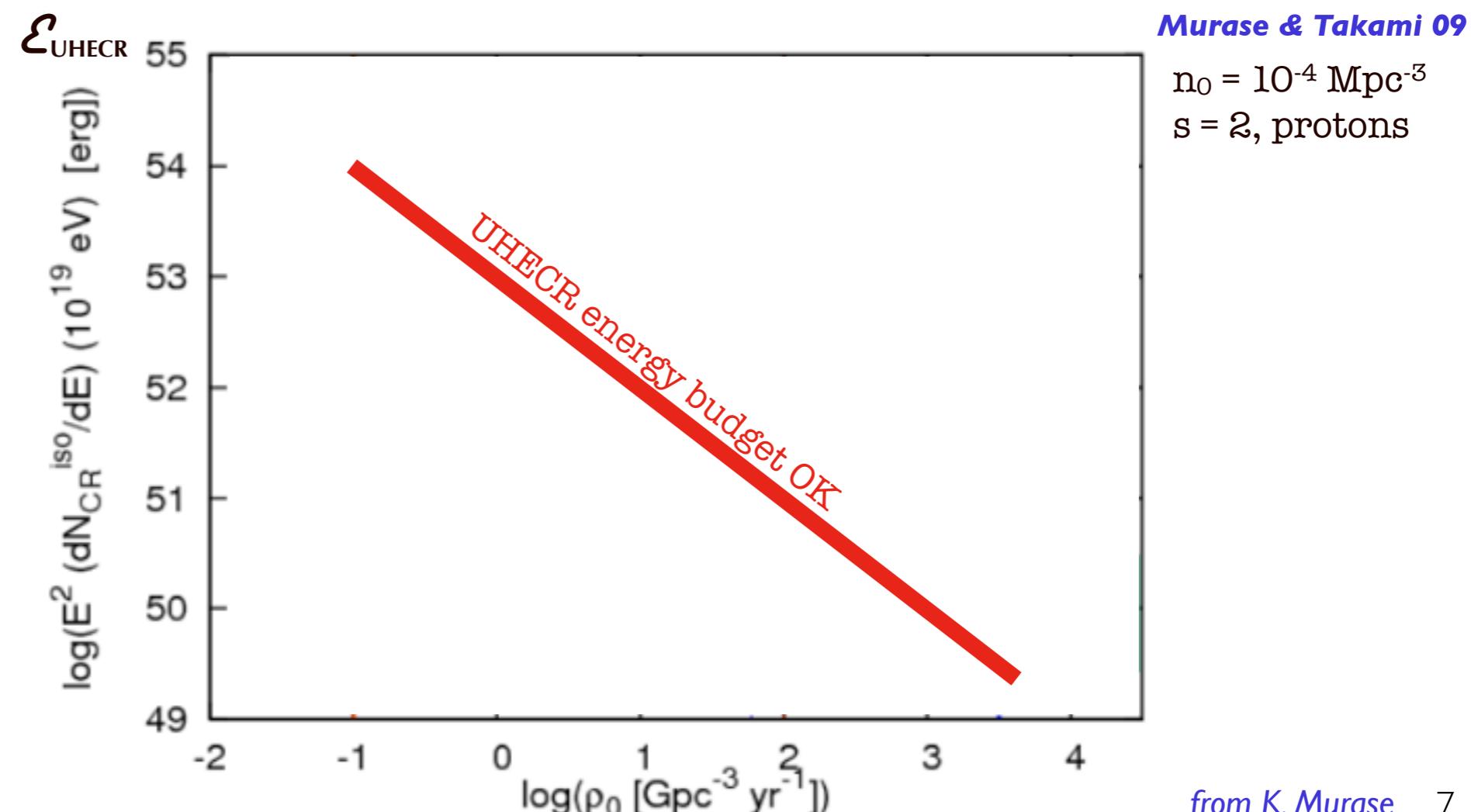
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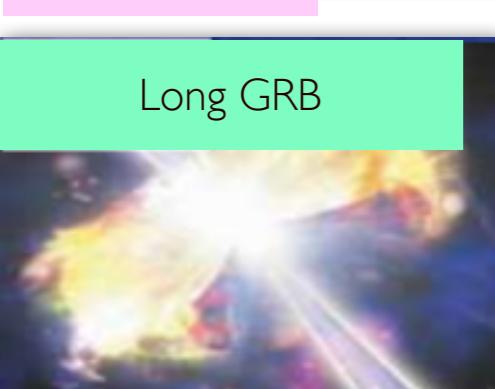
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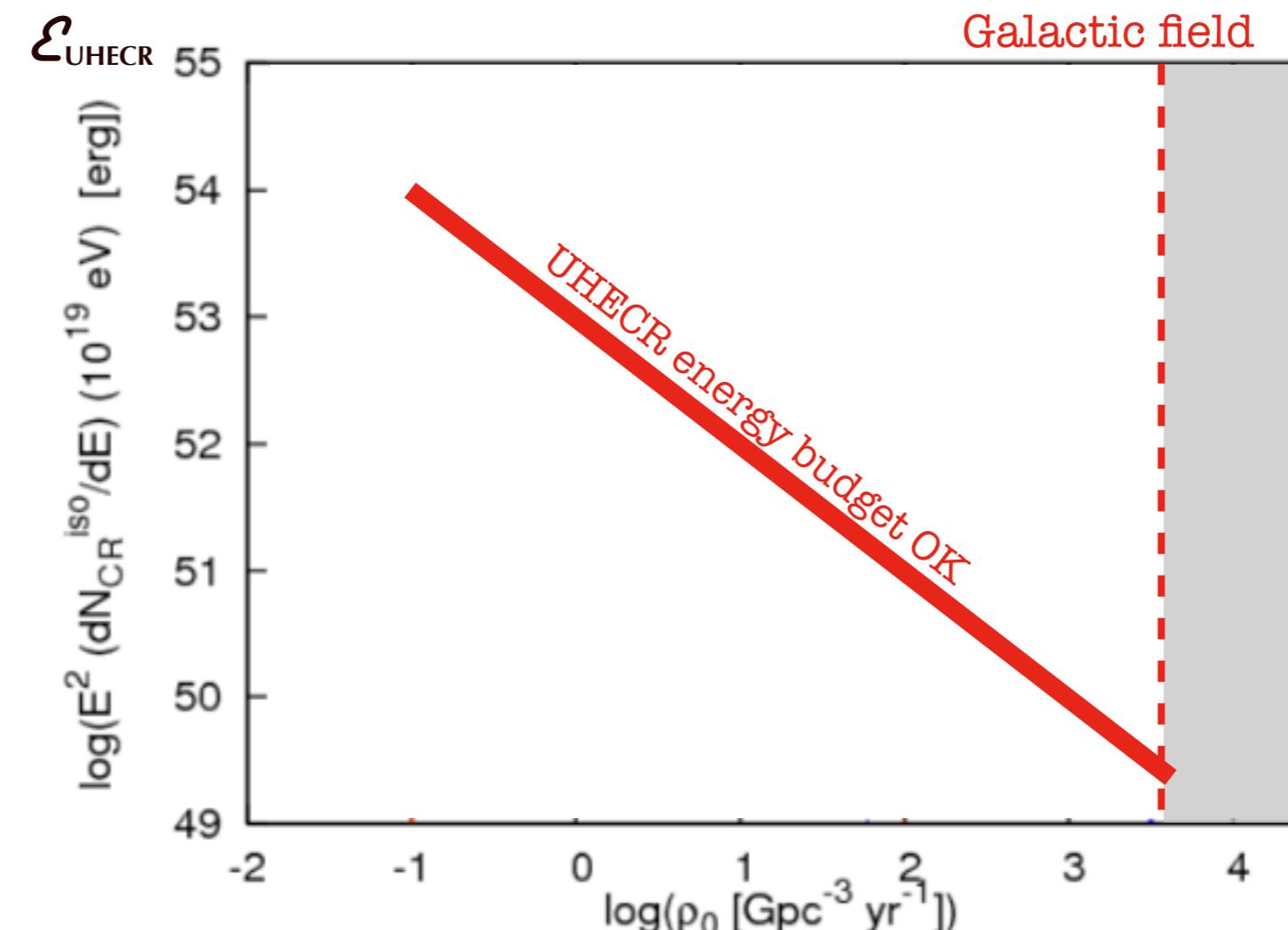
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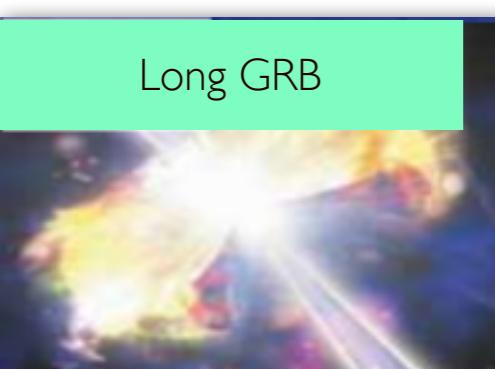
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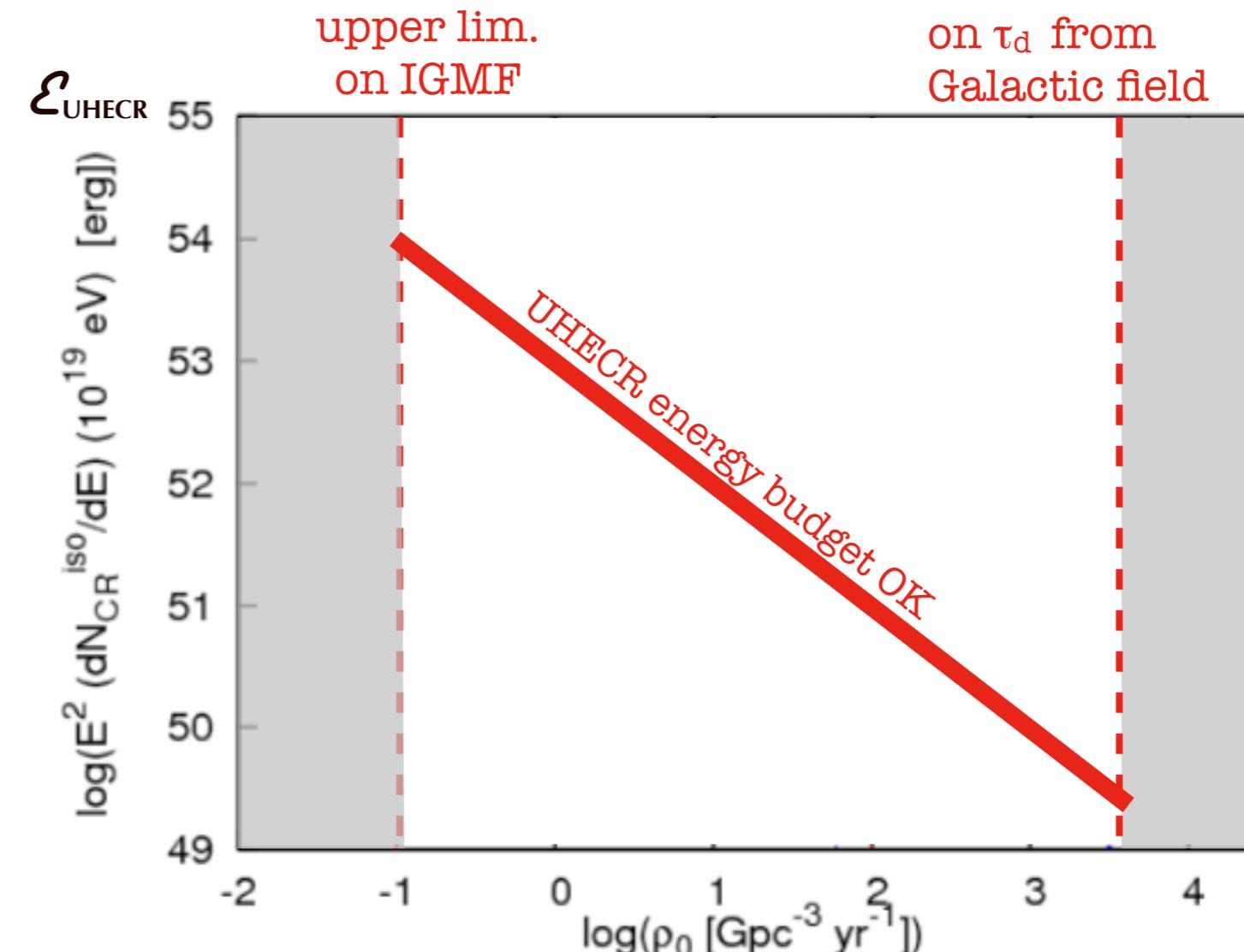
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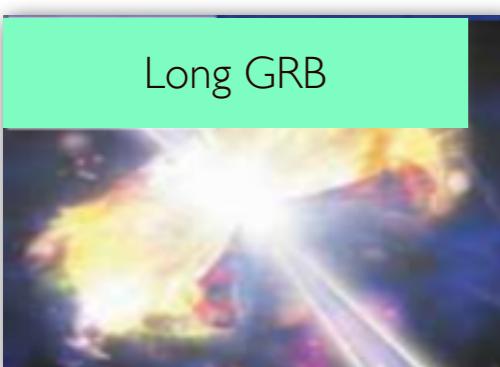
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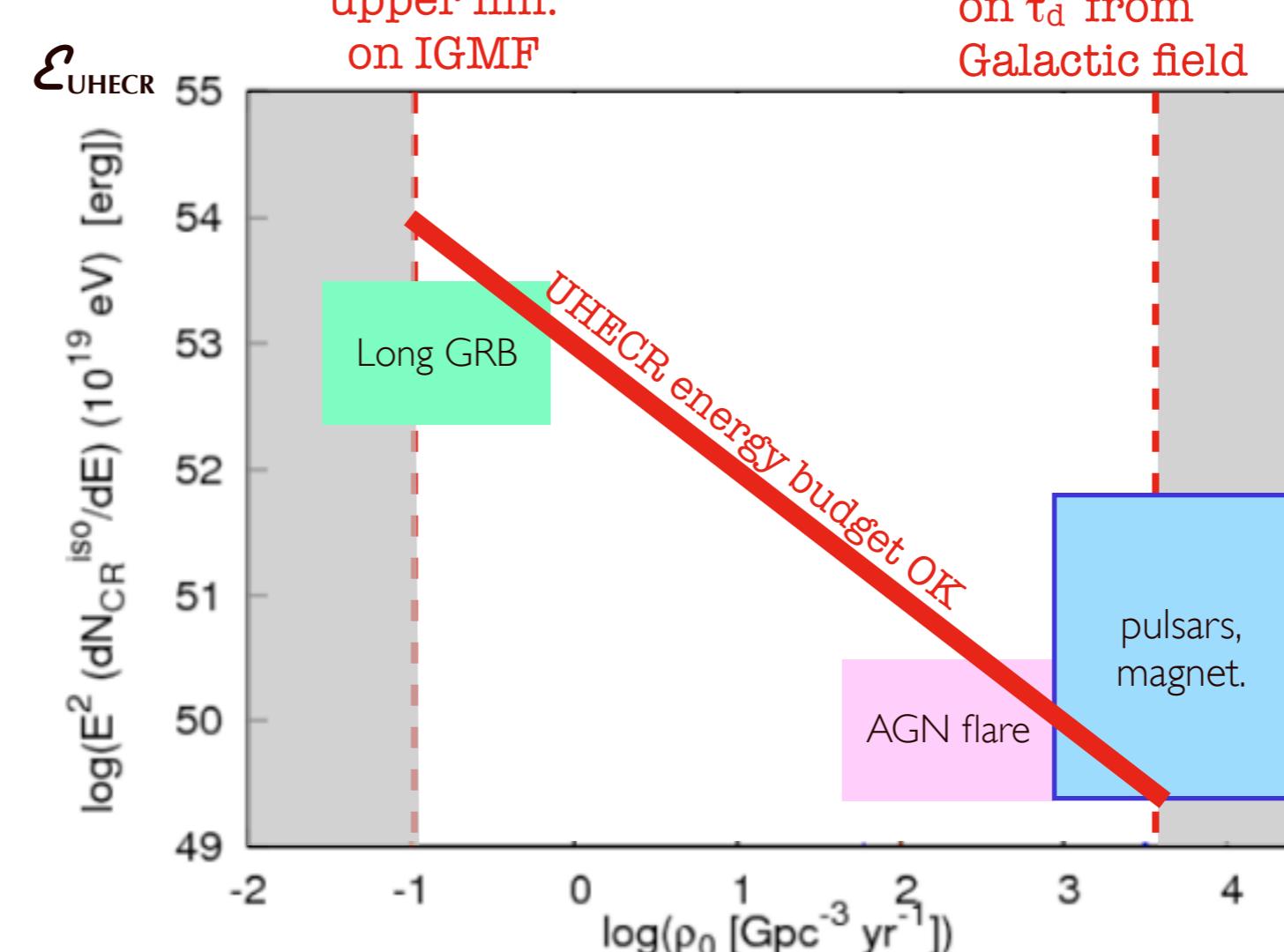
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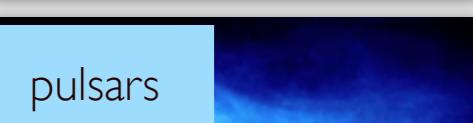
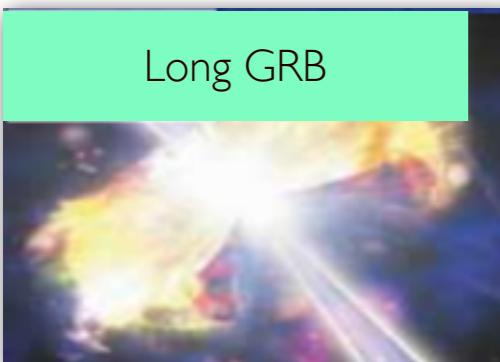
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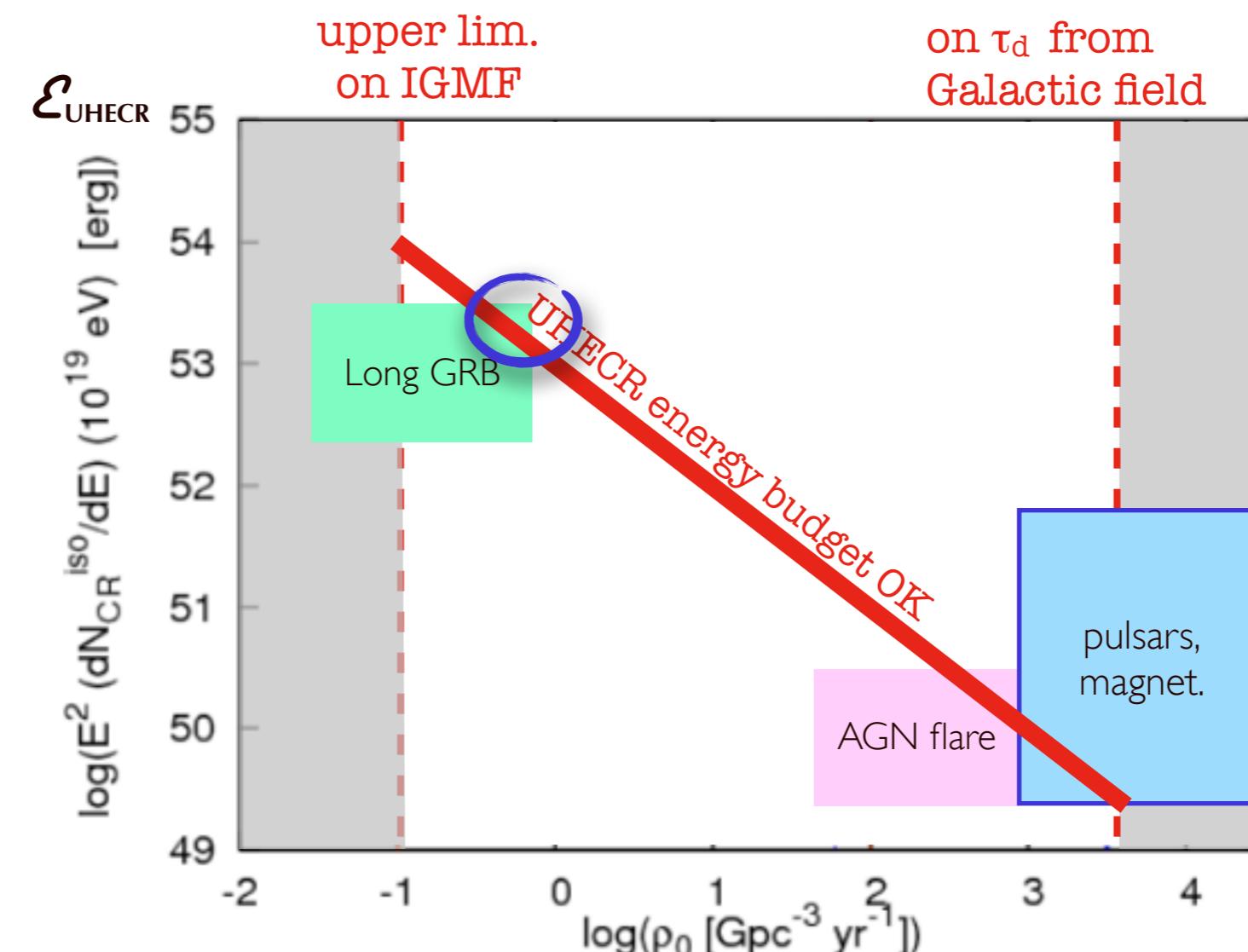
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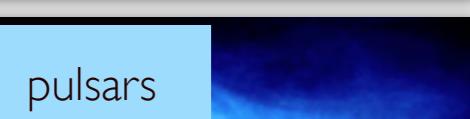
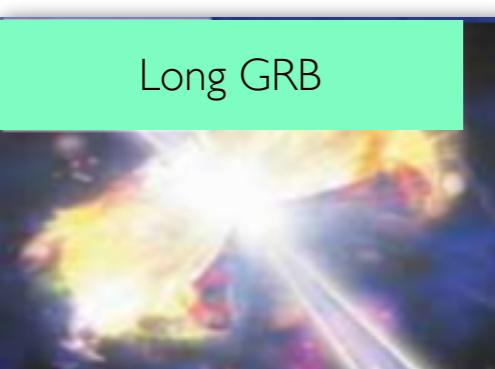
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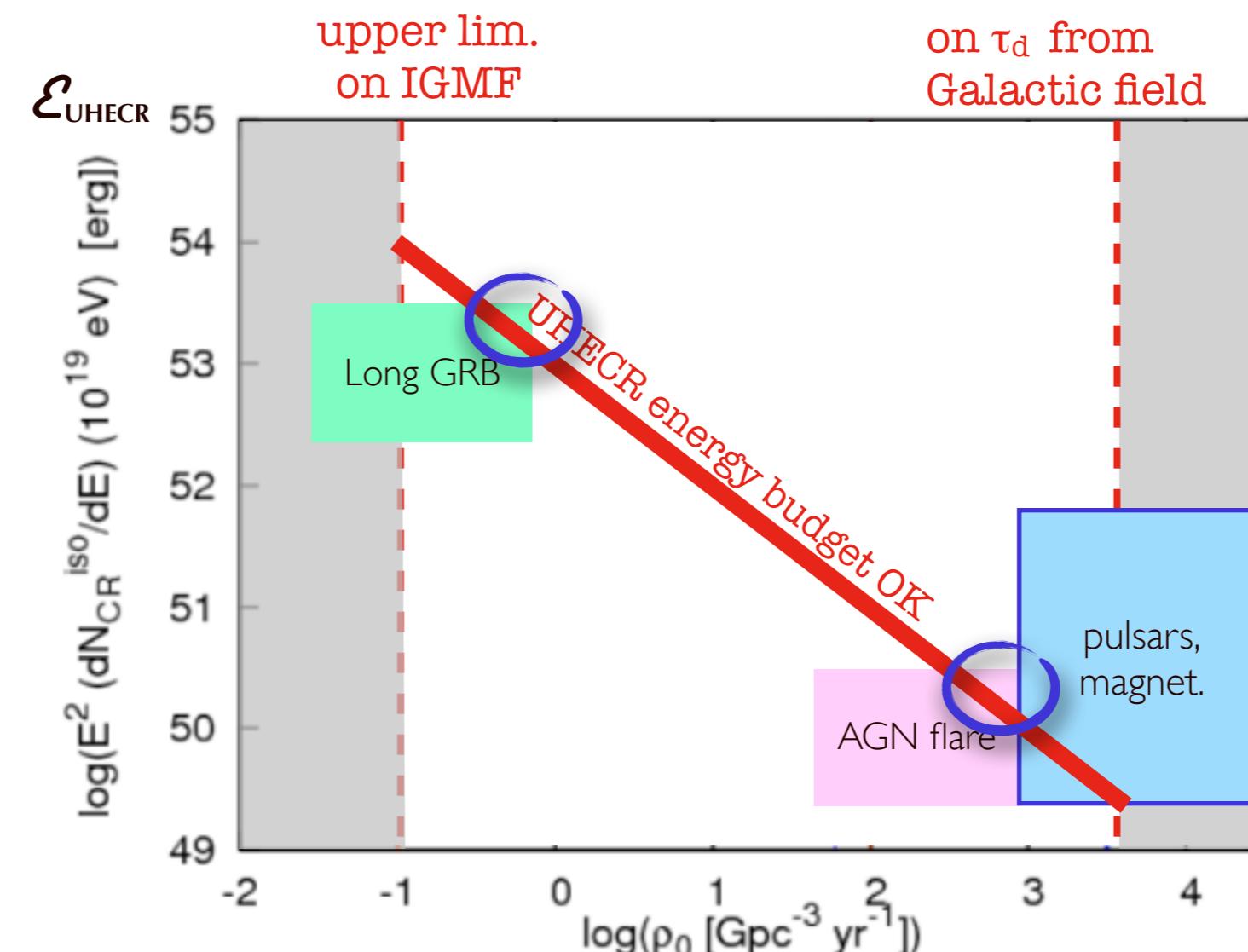
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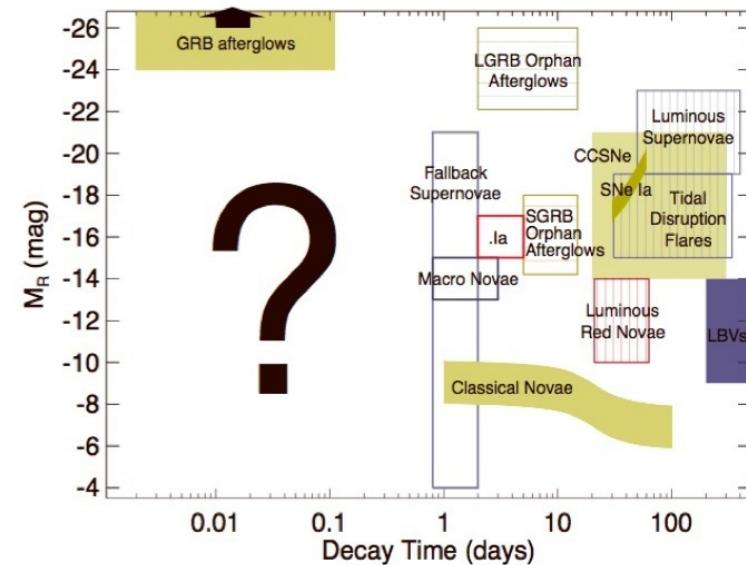
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# Transient sources: the updated zoo

transient sources can mimick a high density source population distribution in the sky due to time delay

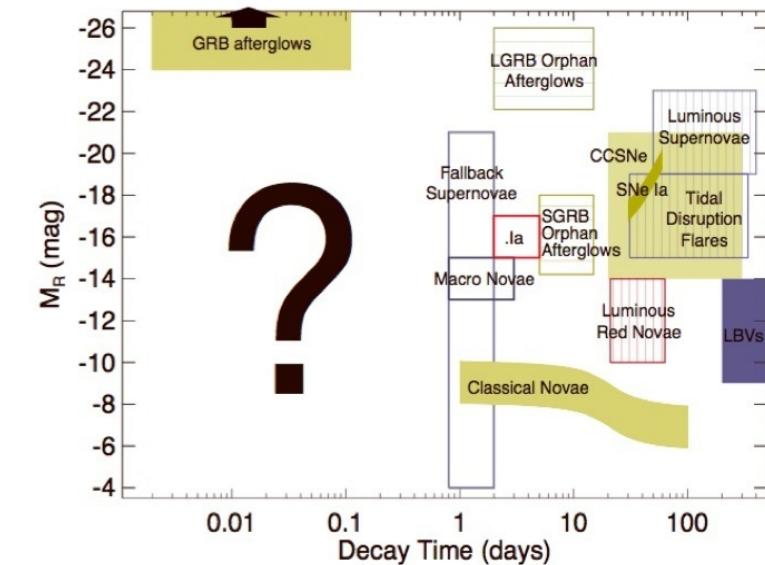
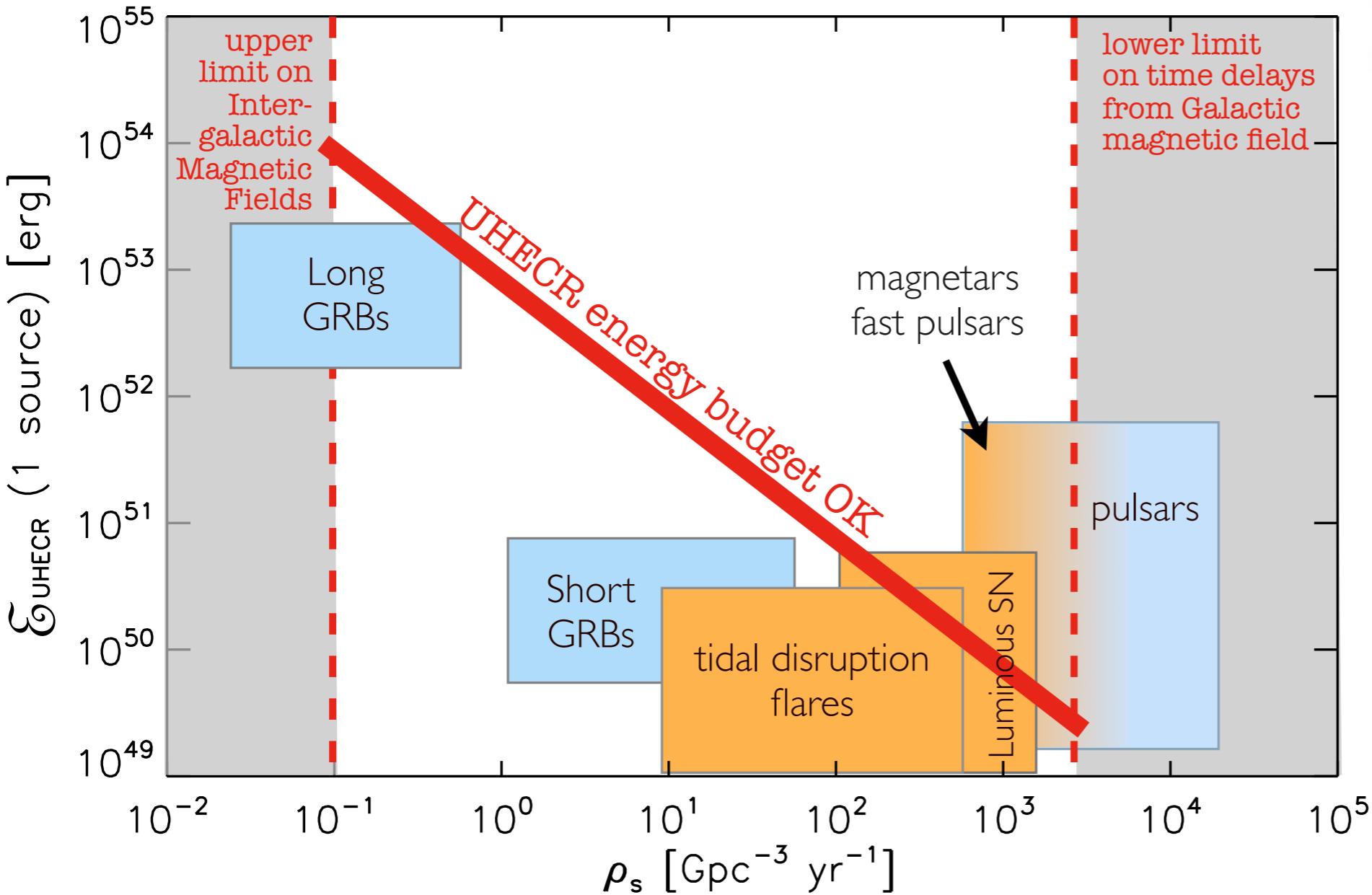


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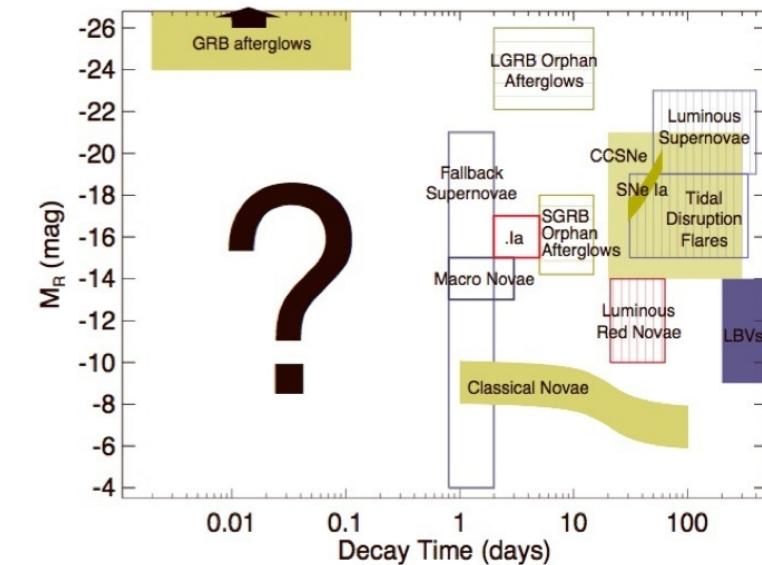
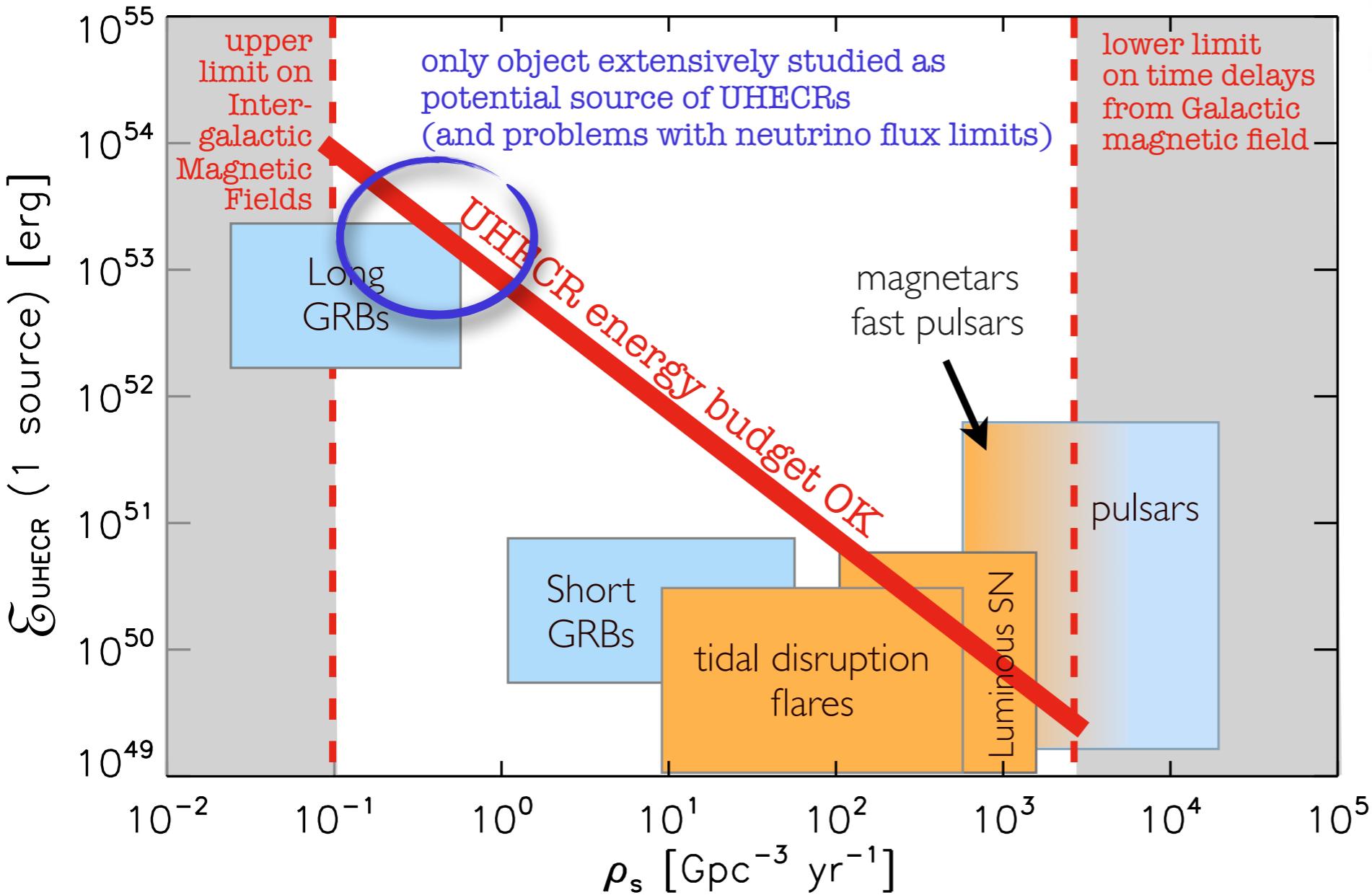
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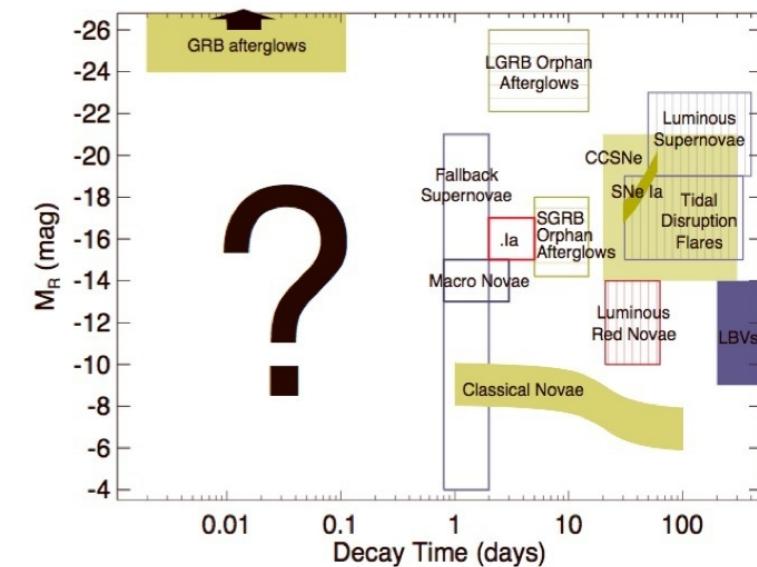
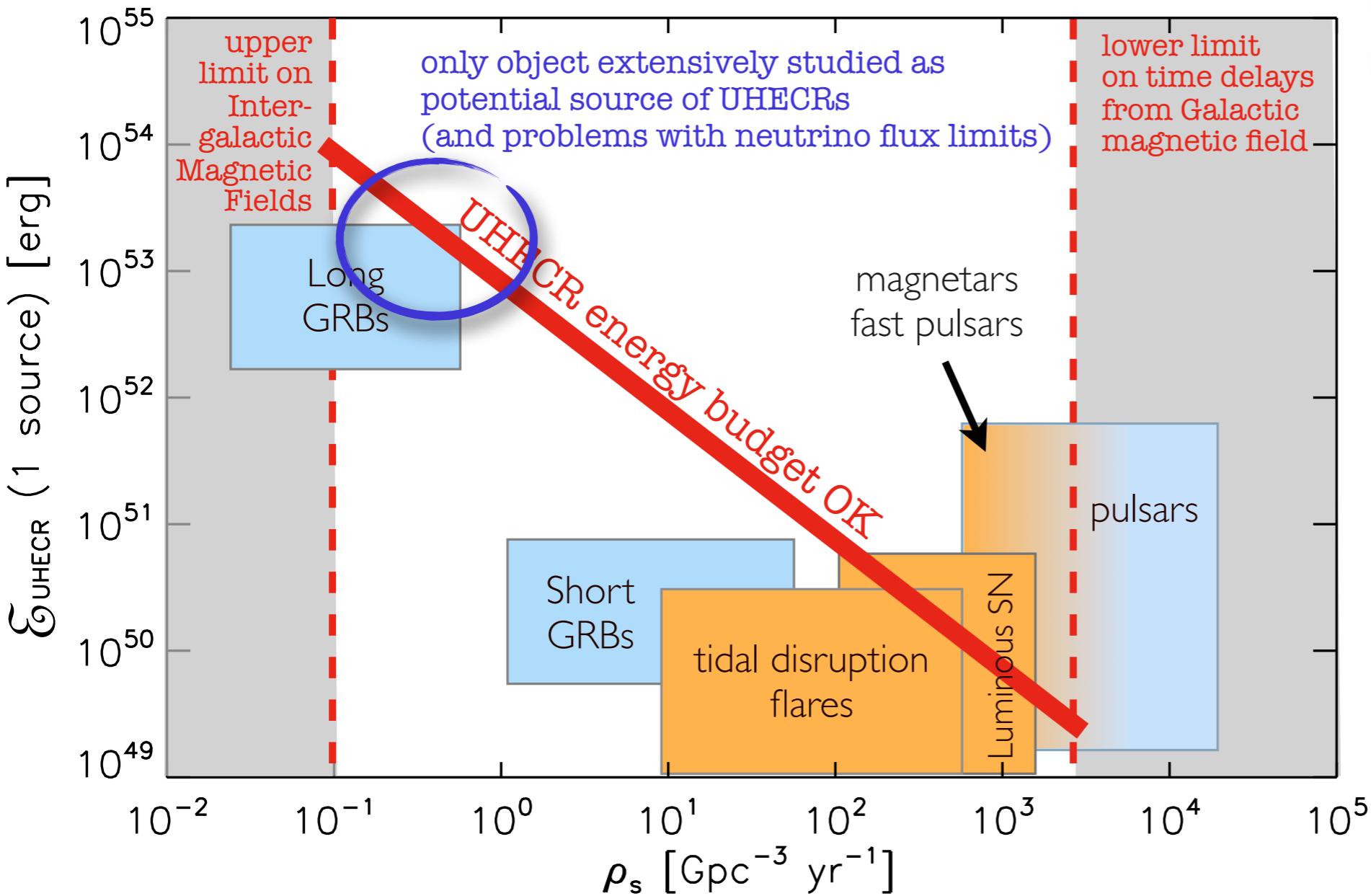
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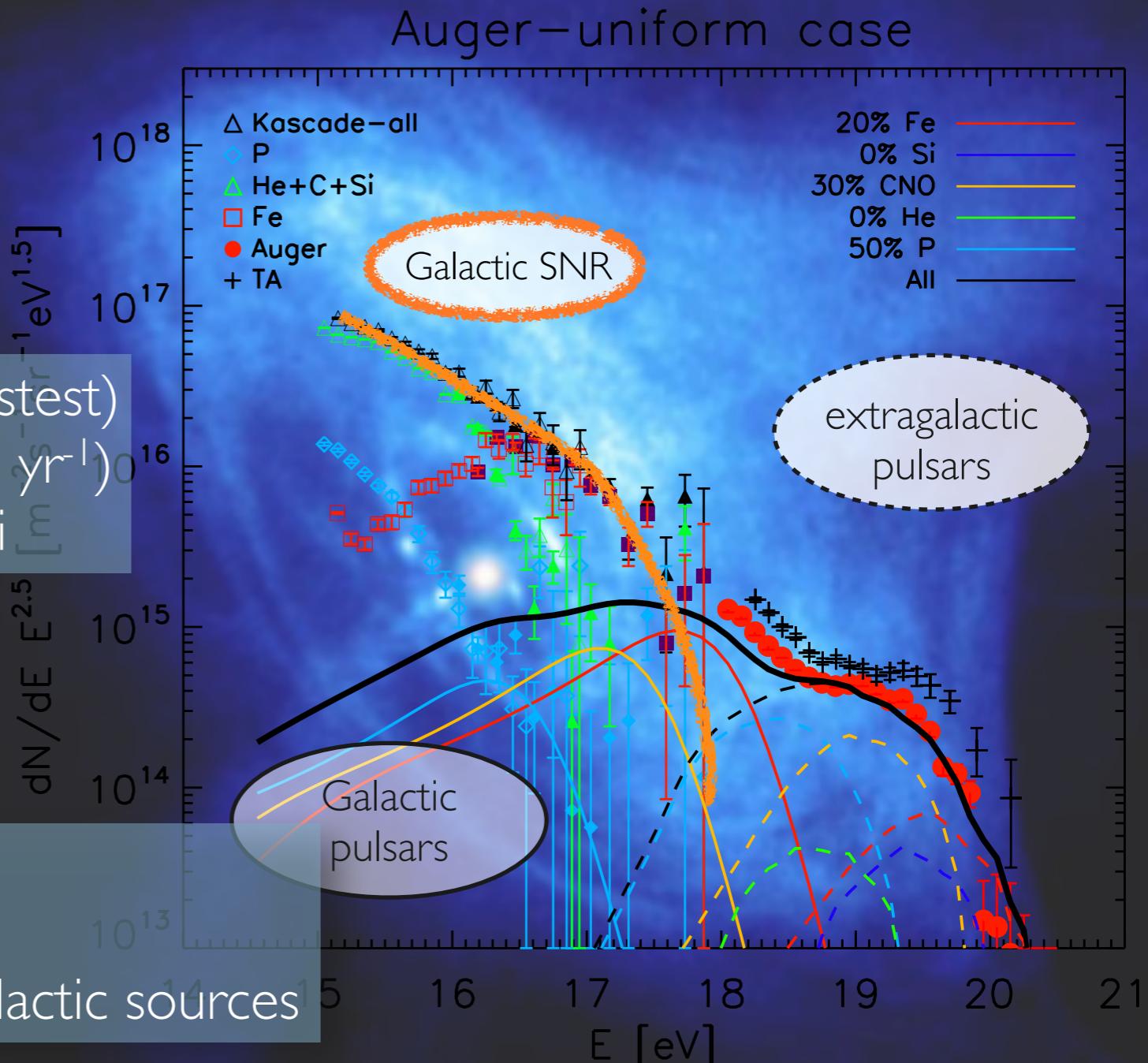
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► idea: use high energy astroparticles to explore a whole bunch of new transients

# UHECRs and pulsars

a model with good initial conditions

- ▶ energetics ( $E_{\text{rot}} > 10^{52}$  erg for the fastest)
- ▶ number density ( $n_{\text{pulsars}} \sim 10^{-4} \text{ Mpc}^{-3} \text{ yr}^{-1}$ )
- ▶ natural spot to produce heavy nuclei



a model that works!

- ▶ fits composition at UHE
- ▶ fits spectrum at UHE
- ▶ bridges gap between SNR - extragalactic sources

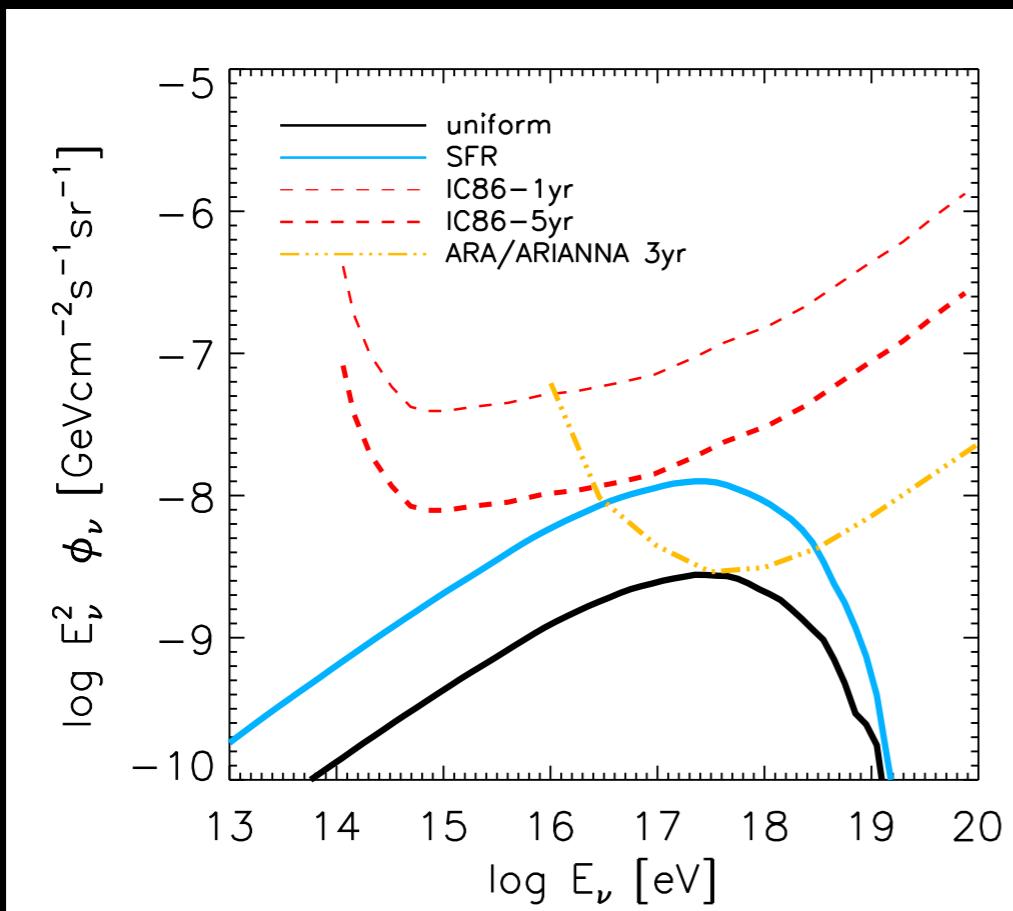
a model producing transient and multi-messenger signals

- ▶ in neutrinos
- ▶ in gravitational waves?
- ▶ Superluminous SNe with X-ray and gamma-ray emissions

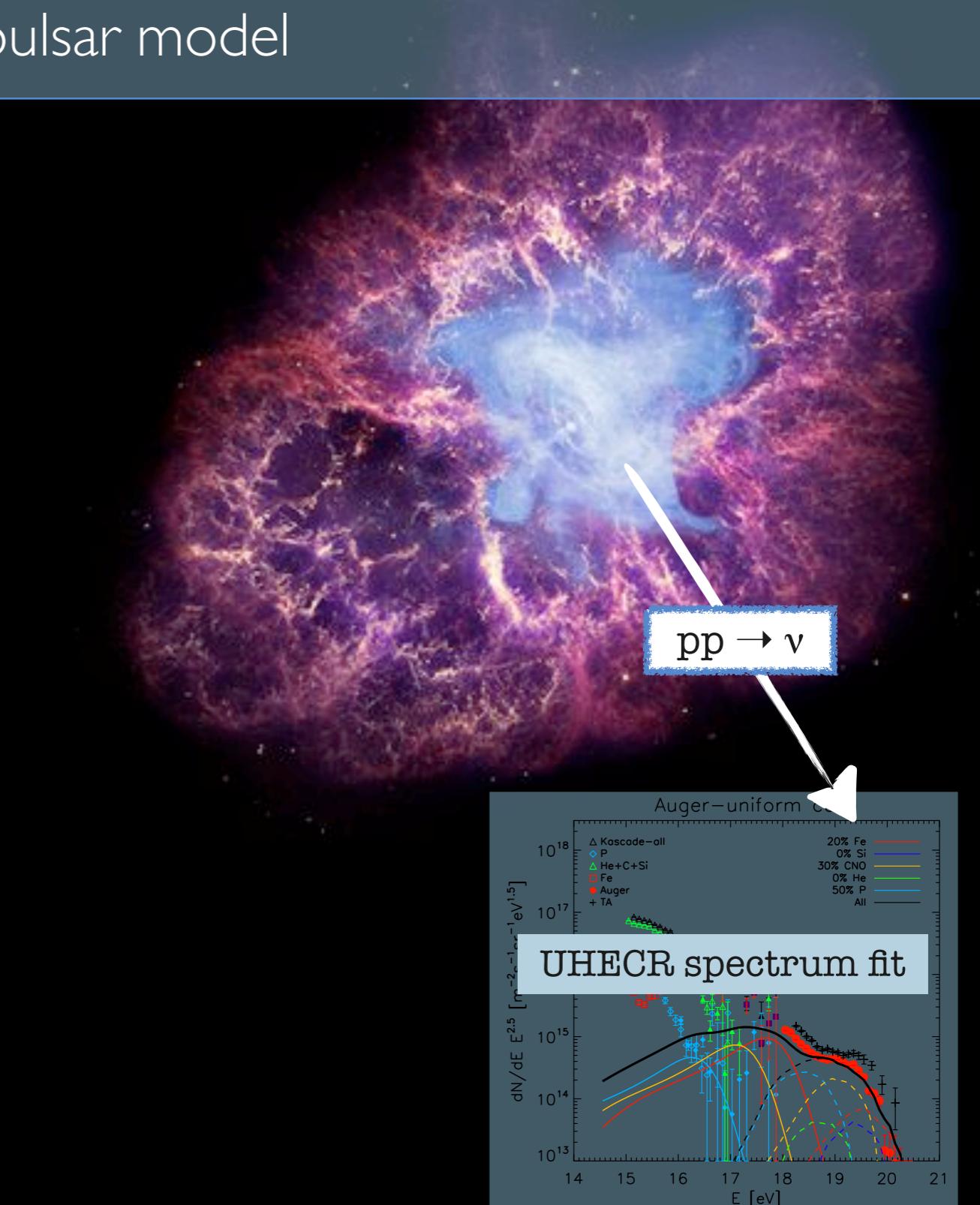
Fang, KK, Olinto 2012, 2013  
Fang, KK, Murase, Olinto 2014  
Fang 2015  
KK 2011  
KK, Amato, Blasi 2015

# Ultrahigh energy neutrinos from the pulsar model

Neutrino flux for population of pulsars  
fitting the UHECR spectrum  
interaction with Supernova ejecta



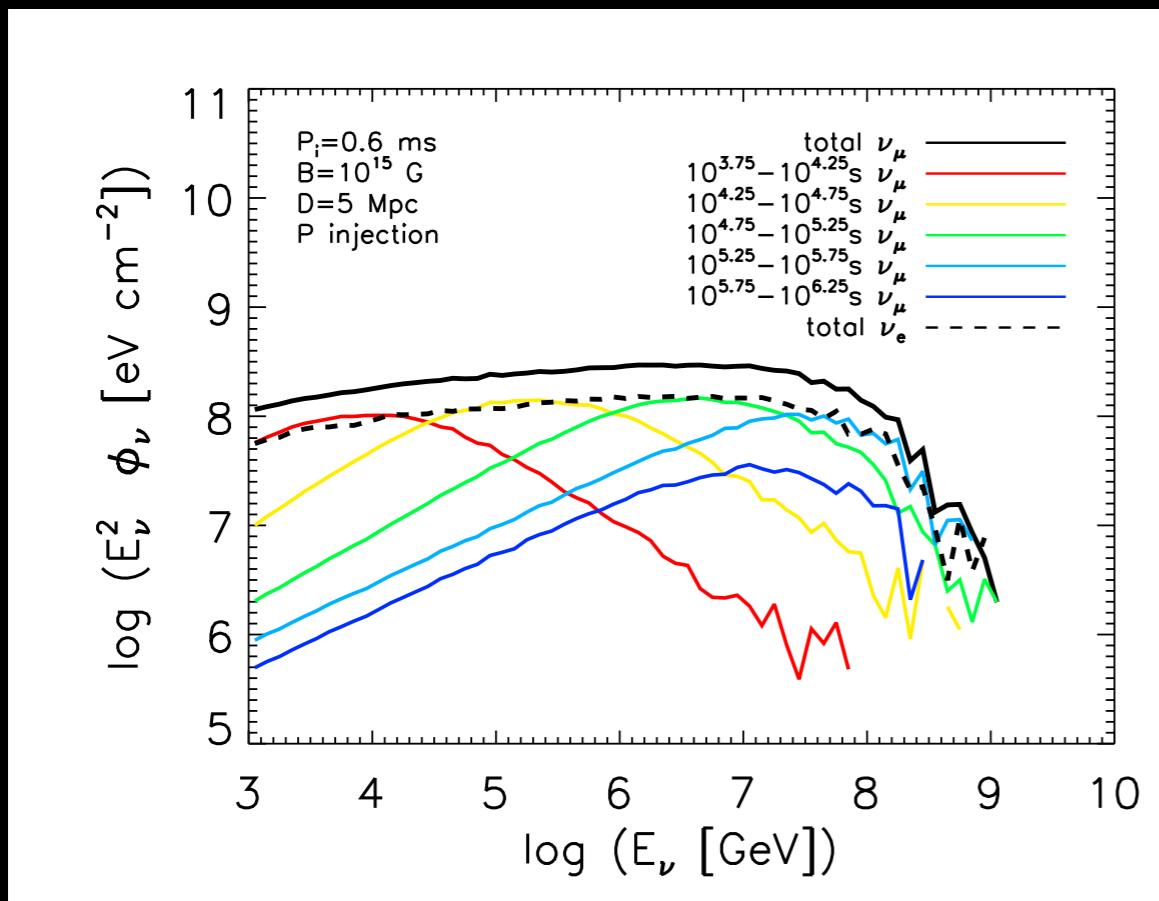
Fang, KK, Murase, Olinto 2015



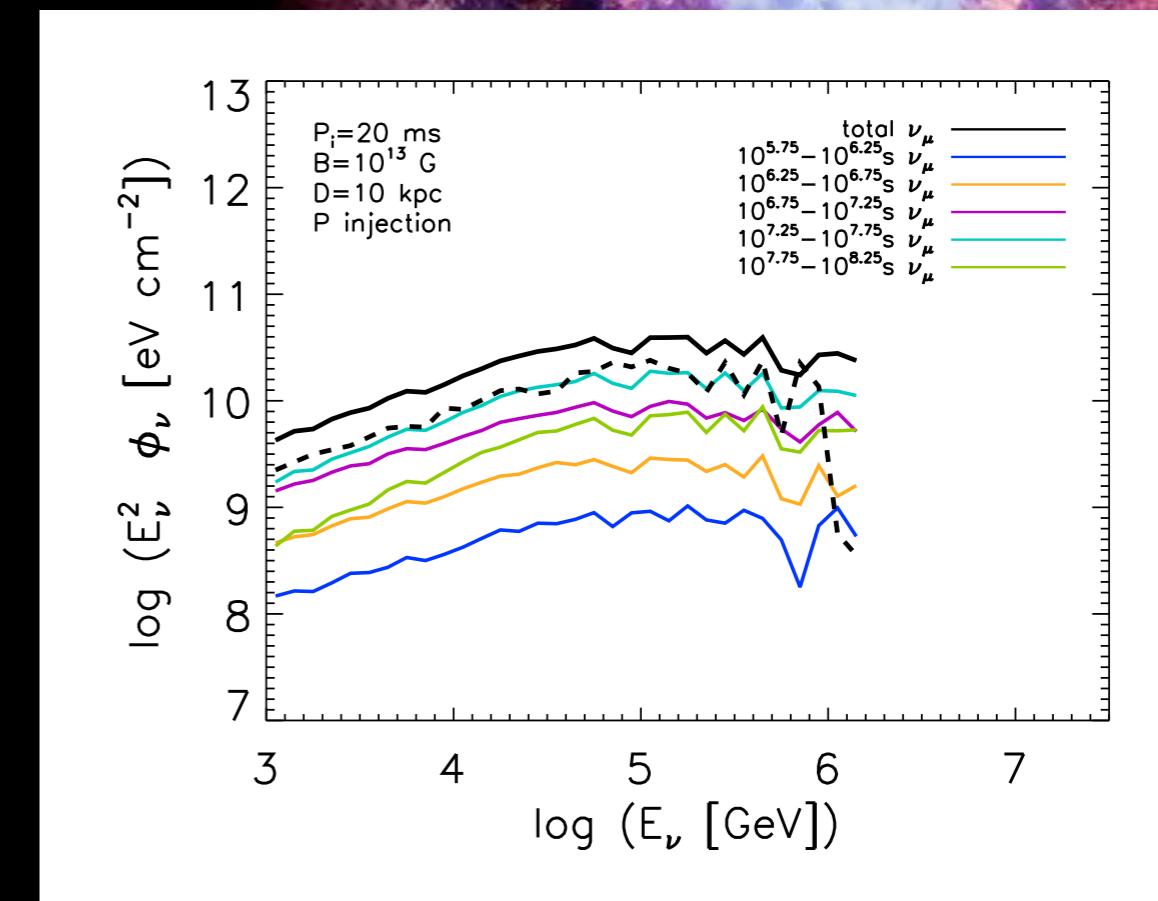
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Fang 2015

magnetar-case



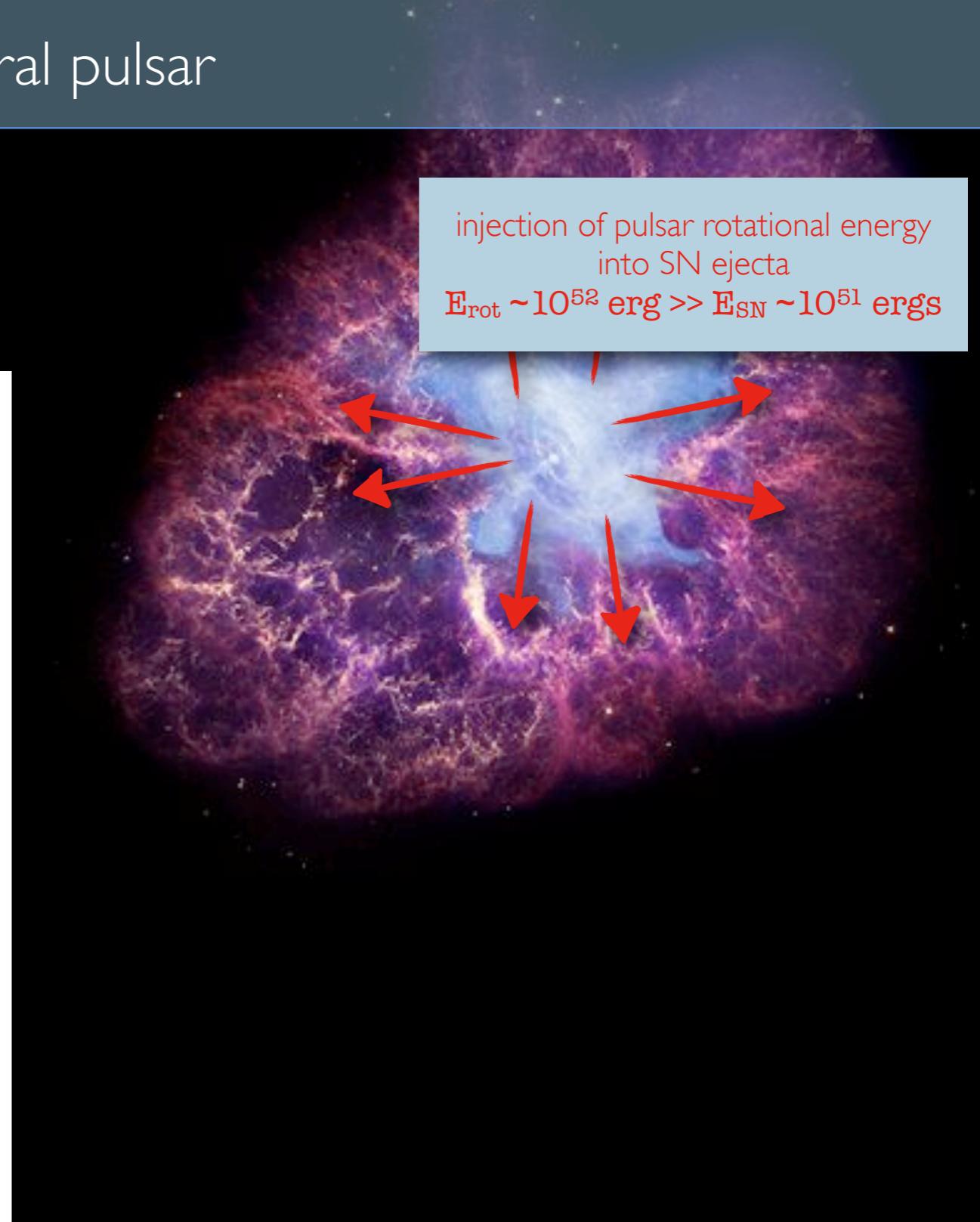
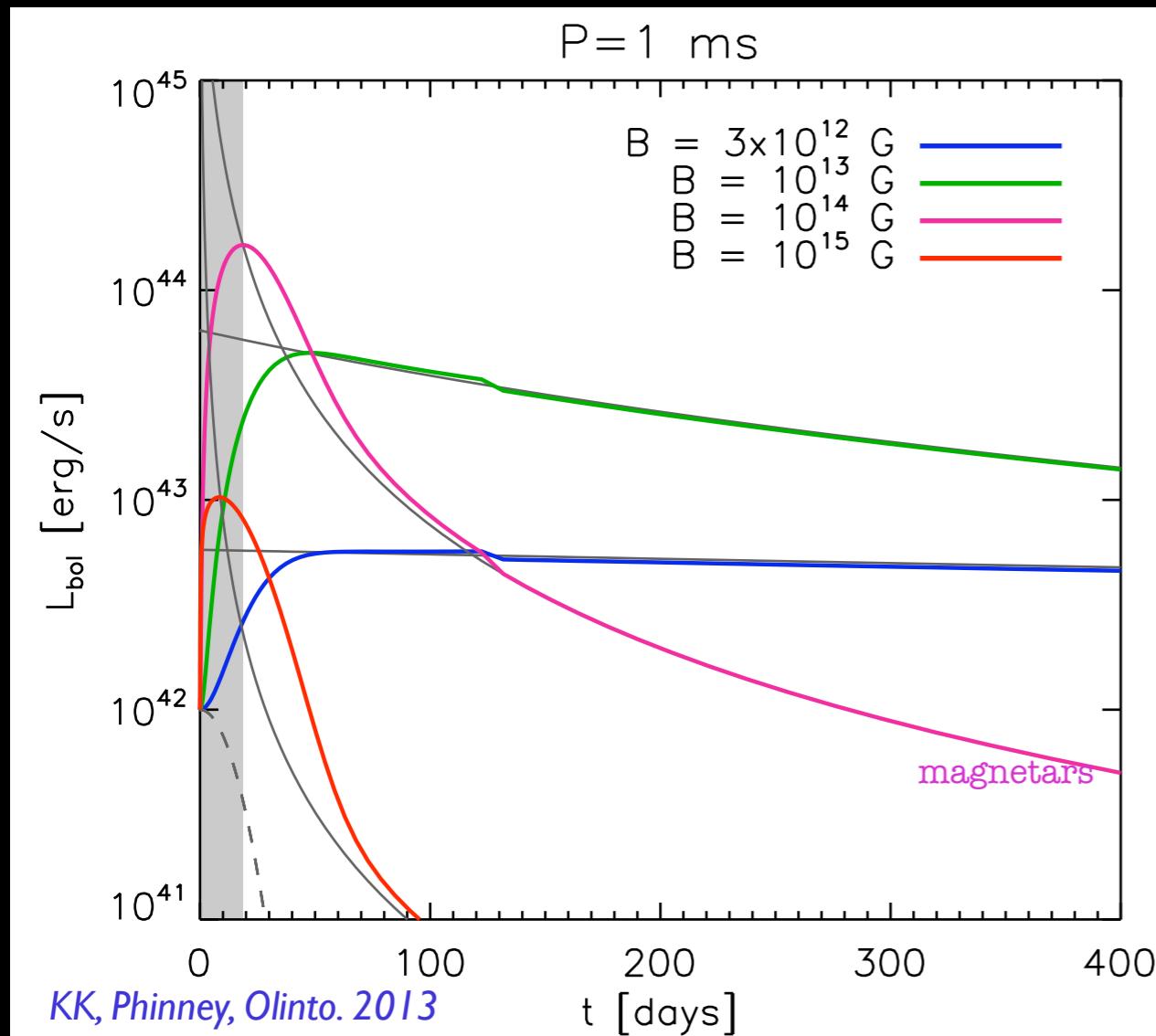
Crab-like-case



# Superluminous supernovae due to central pulsar

- ▶ ultraluminous supernovae lasting over a few months/years

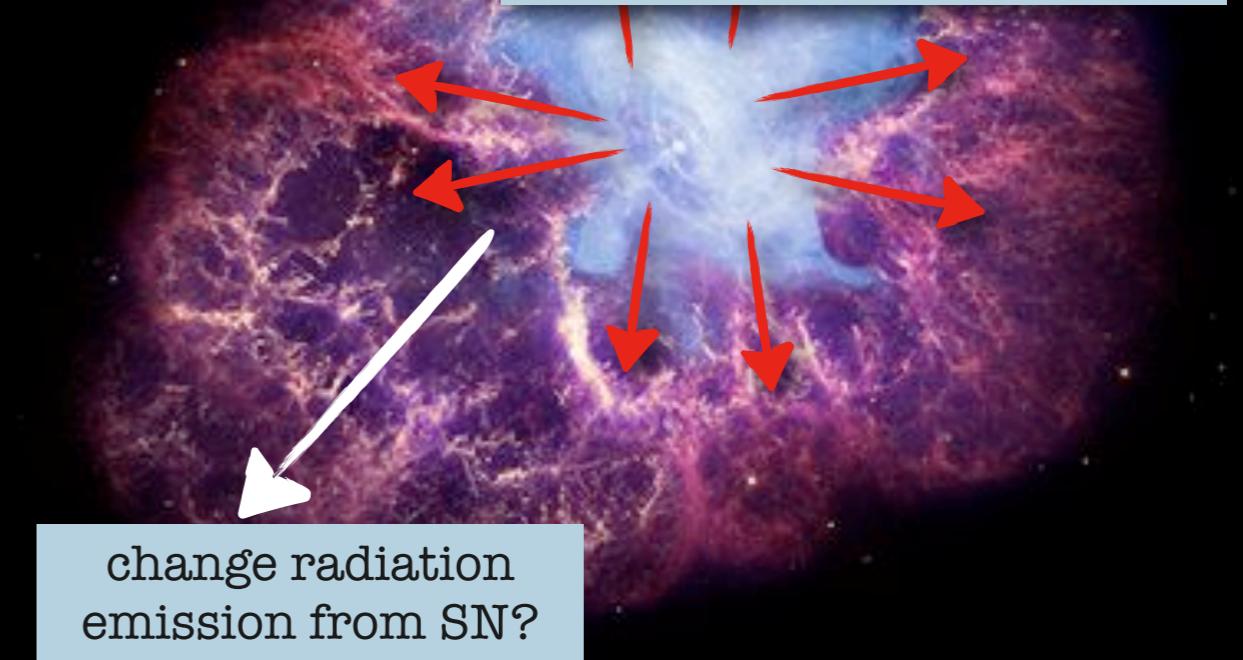
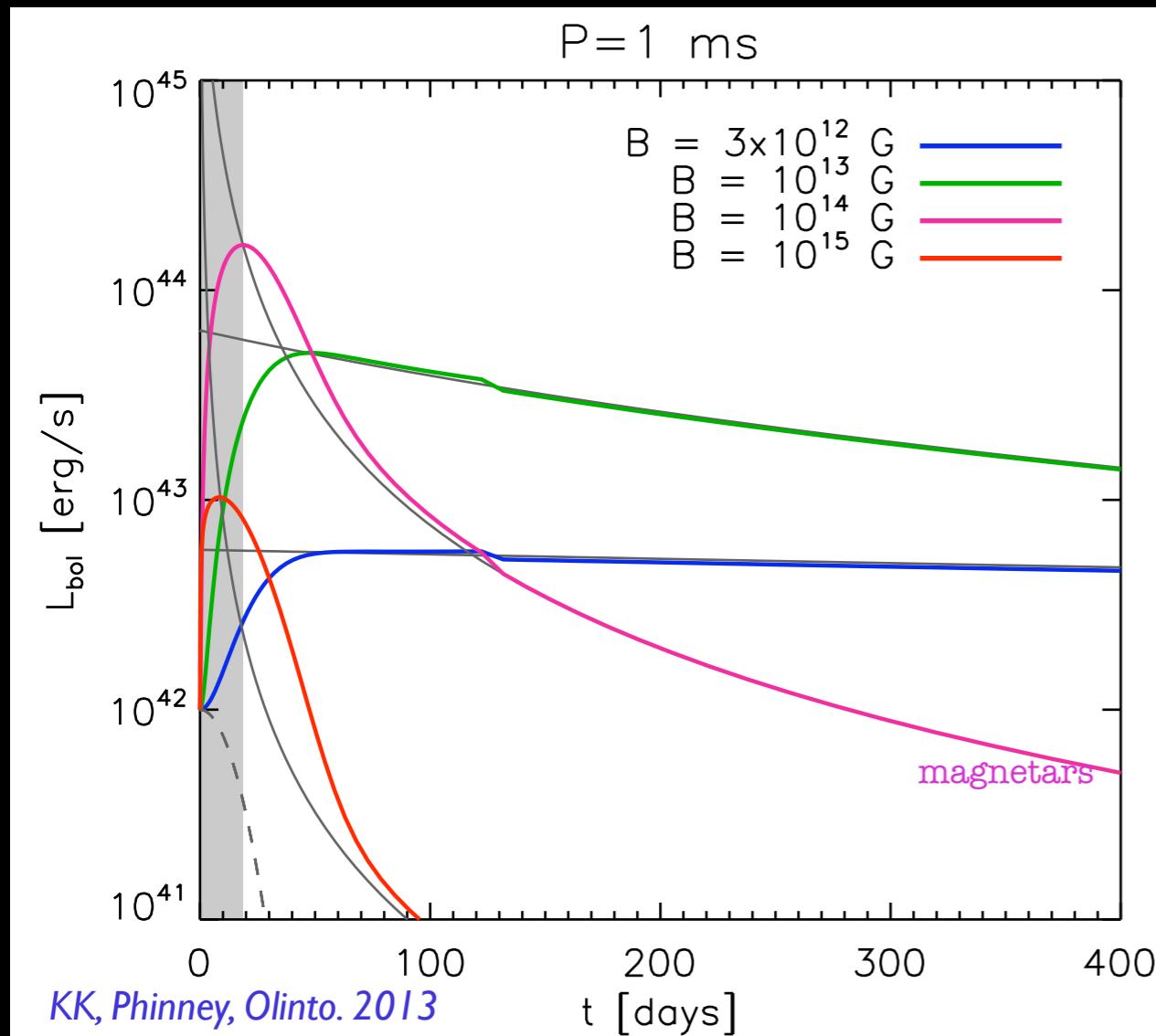
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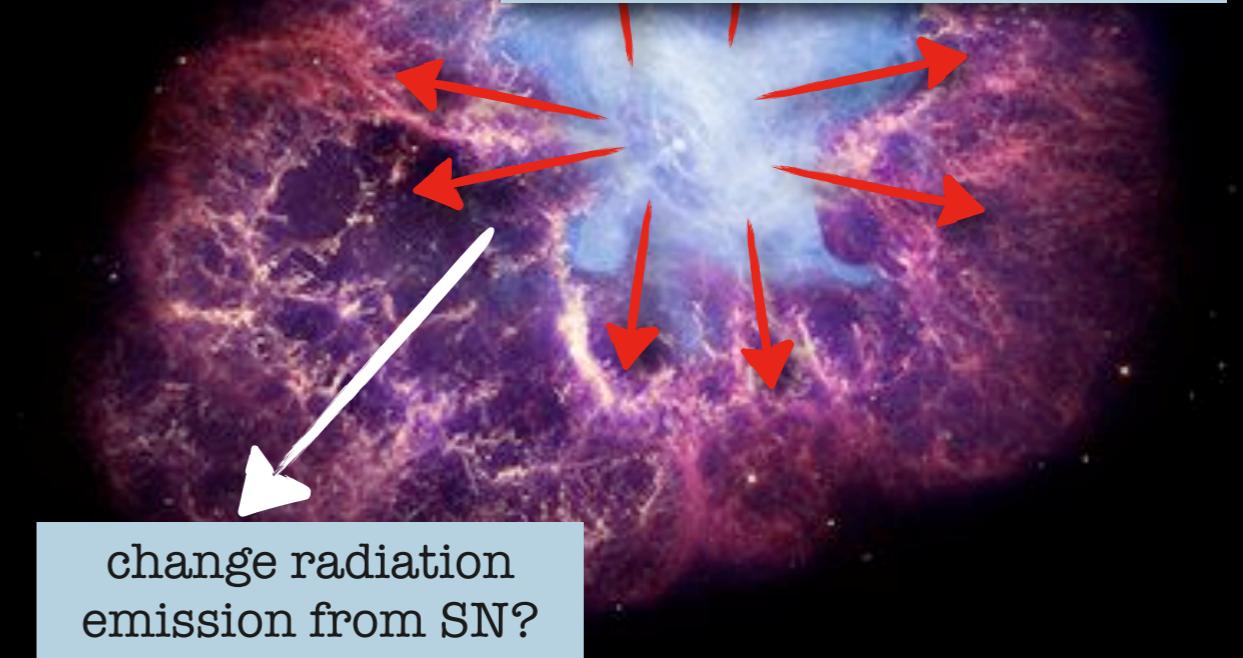
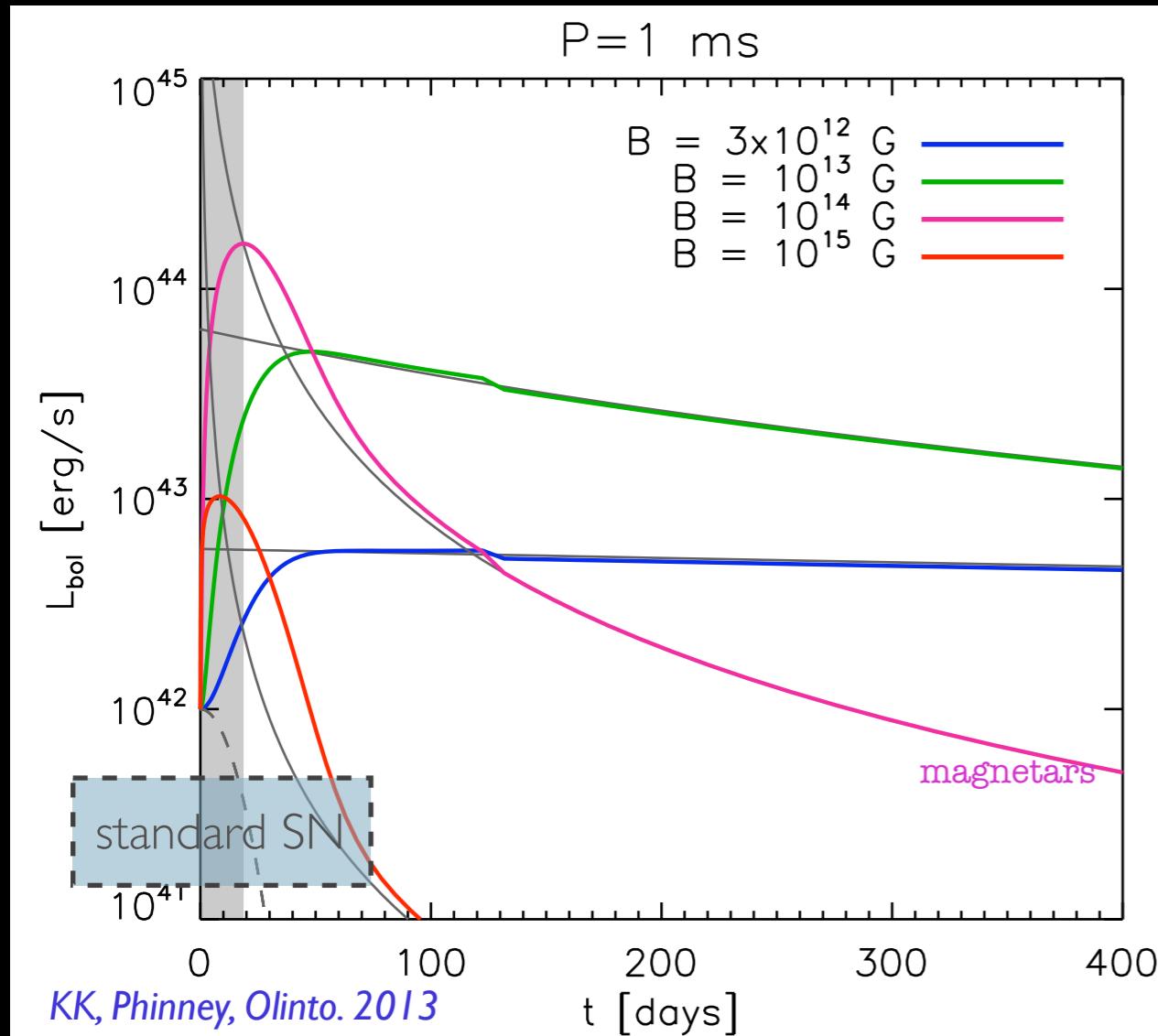
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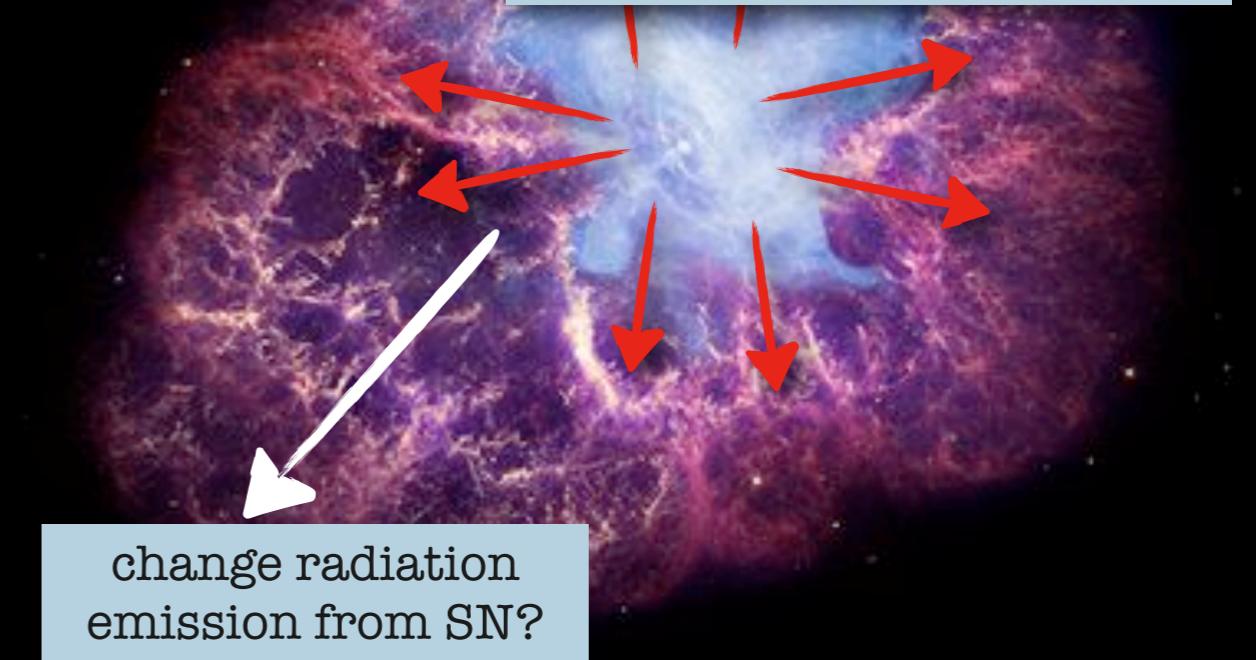
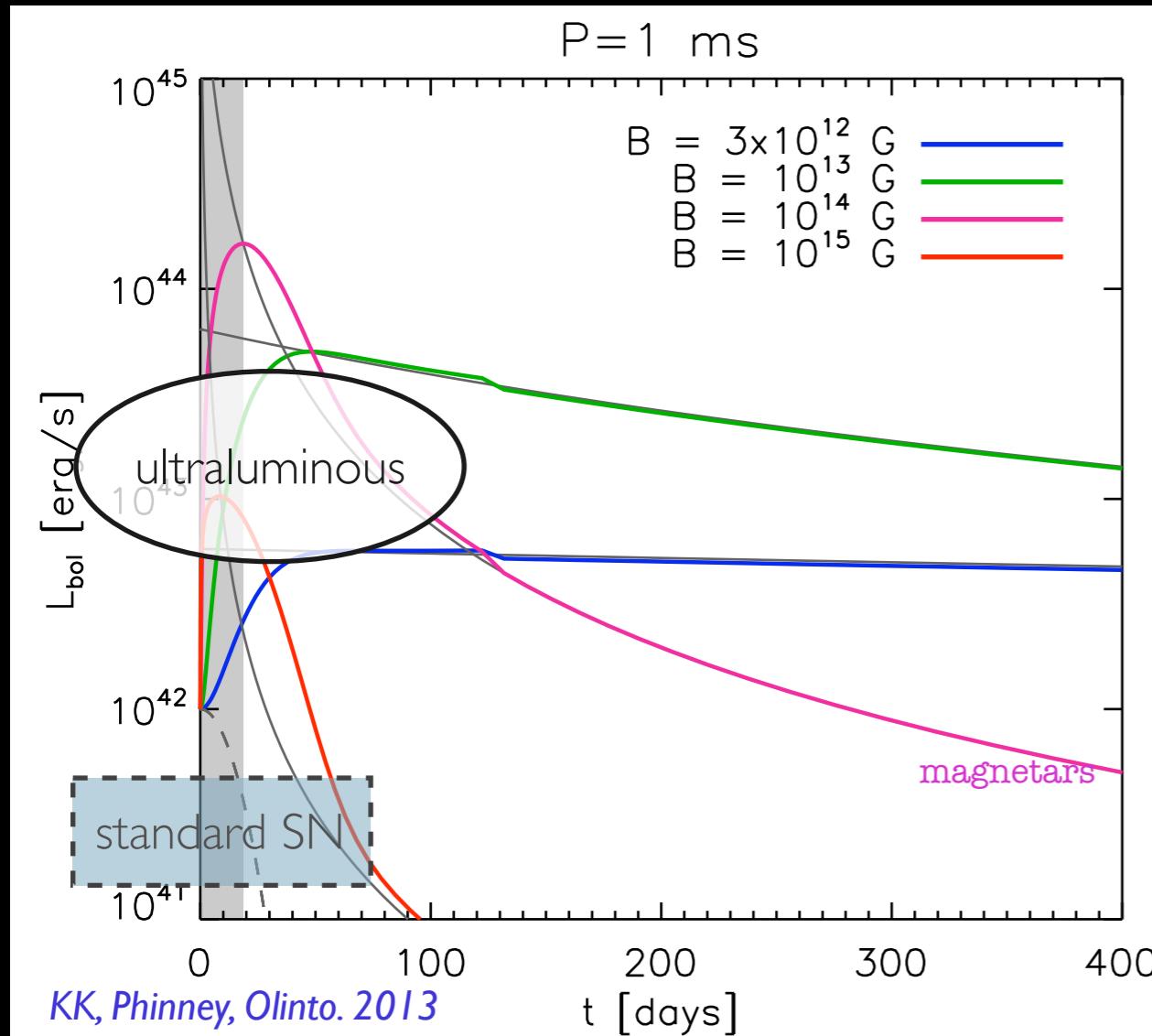
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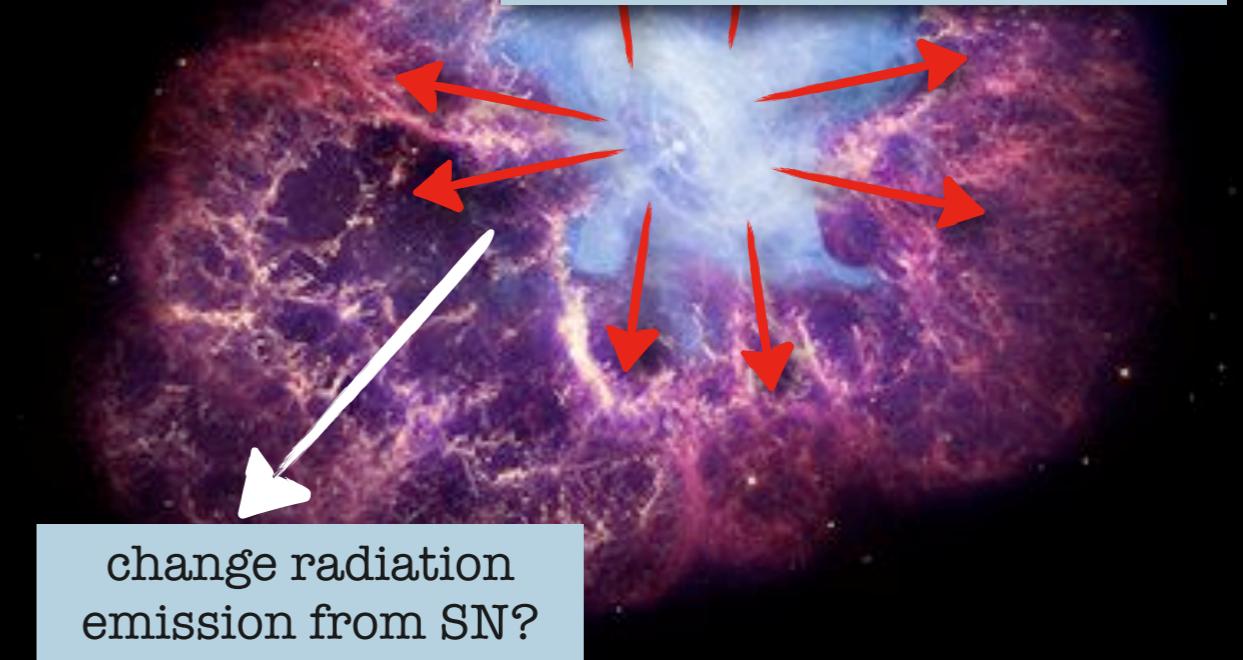
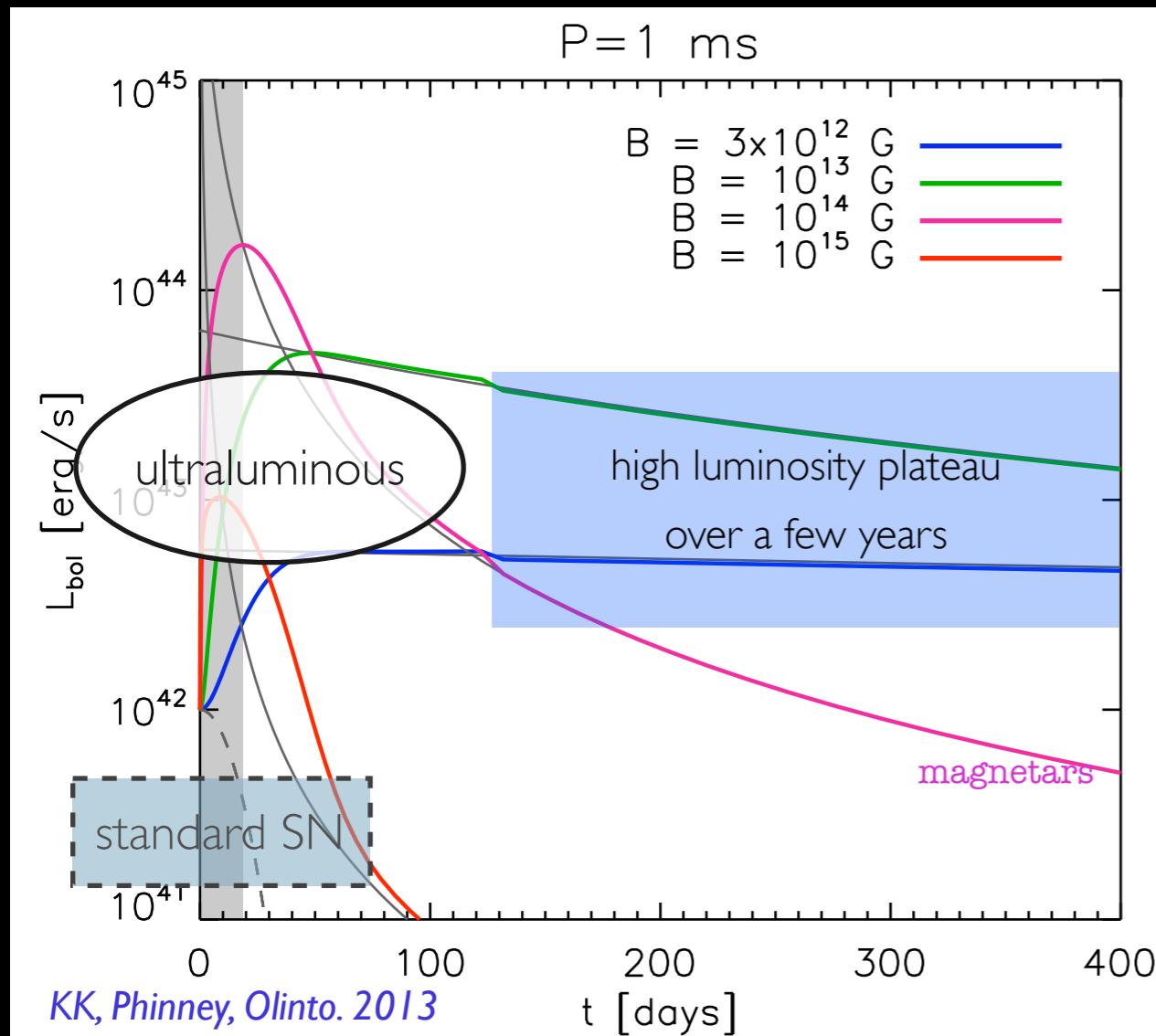
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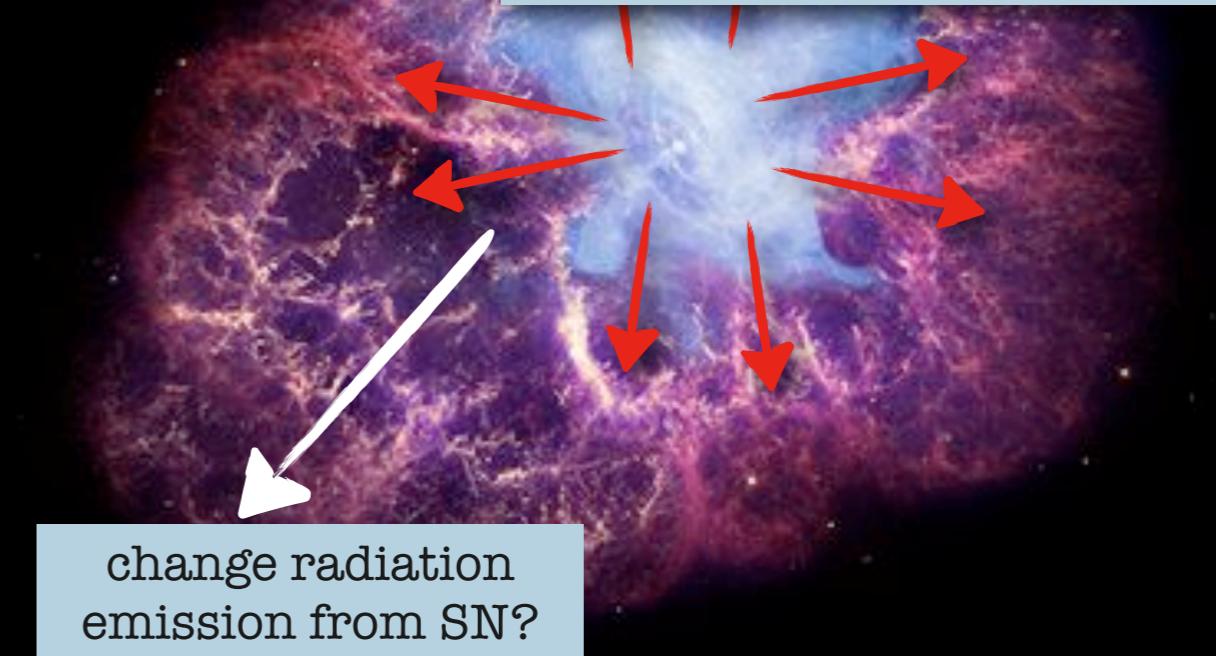
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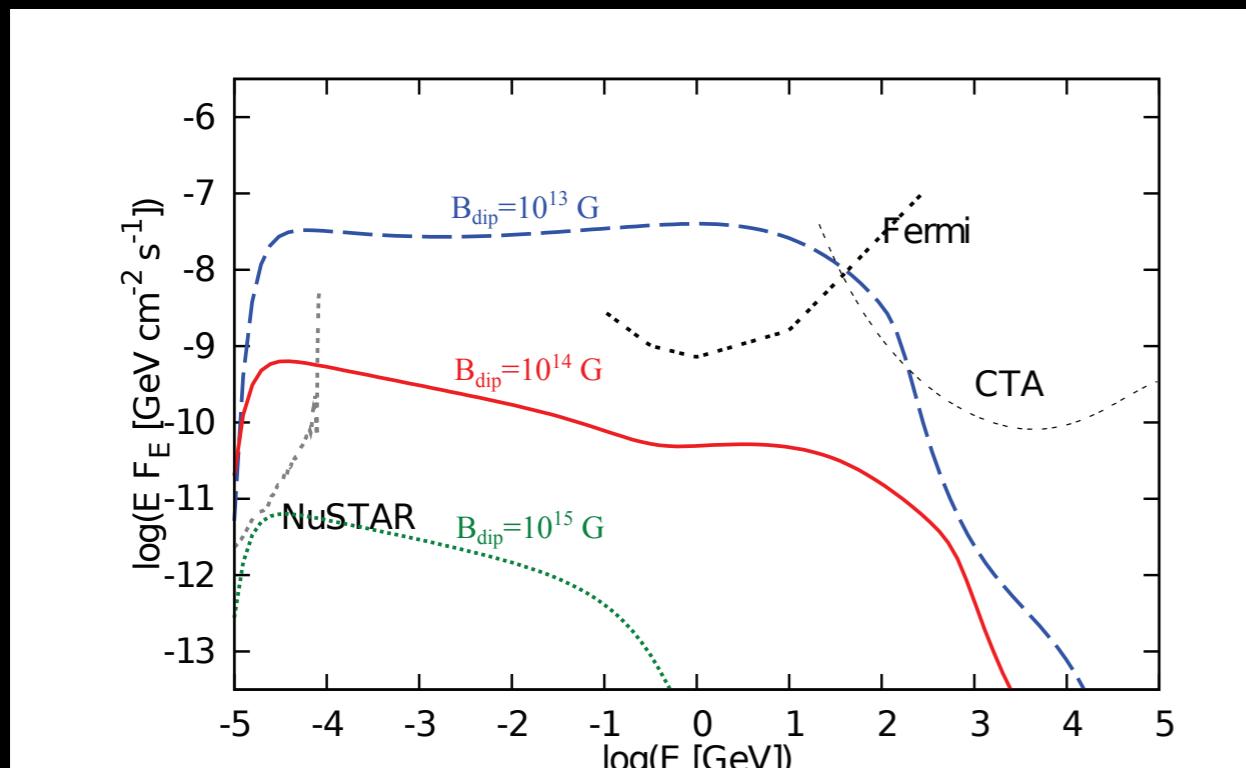
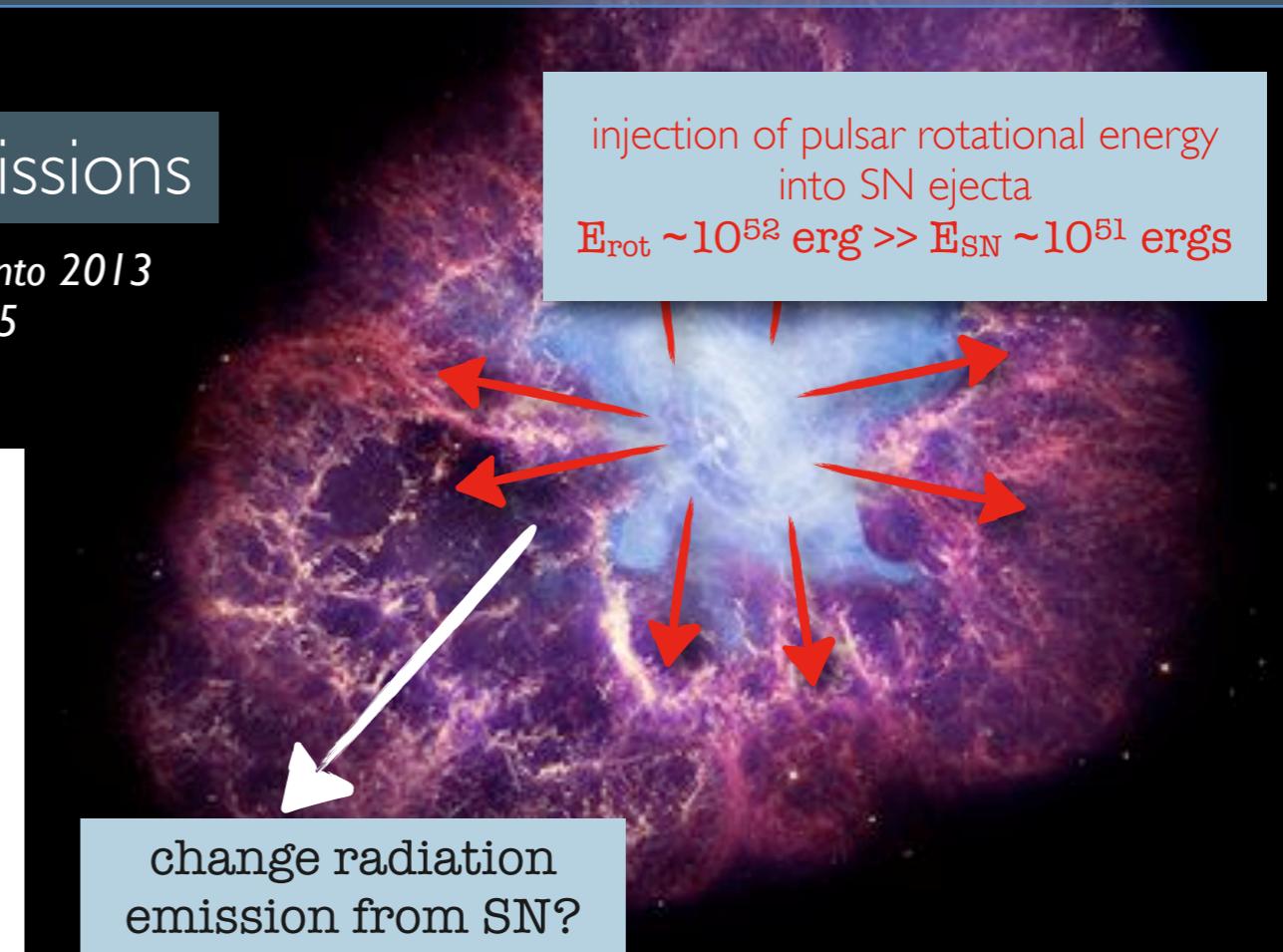


FIG. 7.— High-energy photon spectra of the early PWN embedded in the SN ejecta for  $P_i = 2 \text{ ms}$  at  $t = 10^{7.5} \text{ s} \simeq 316 \text{ d}$ . Different magnetic field strengths are considered. Detections with CTA are possible for  $B_{\text{dip}} = 10^{13} \text{ G}$ .

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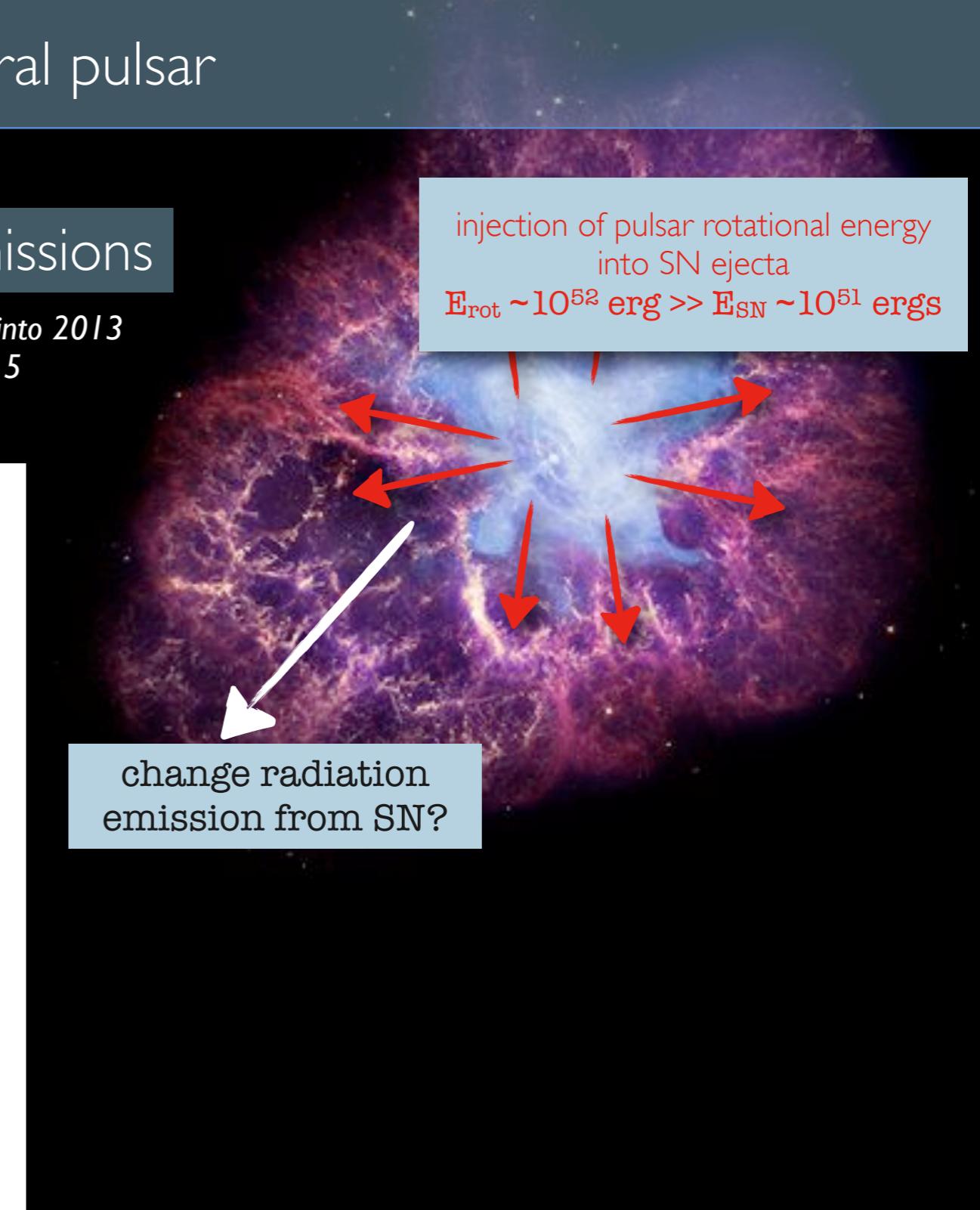
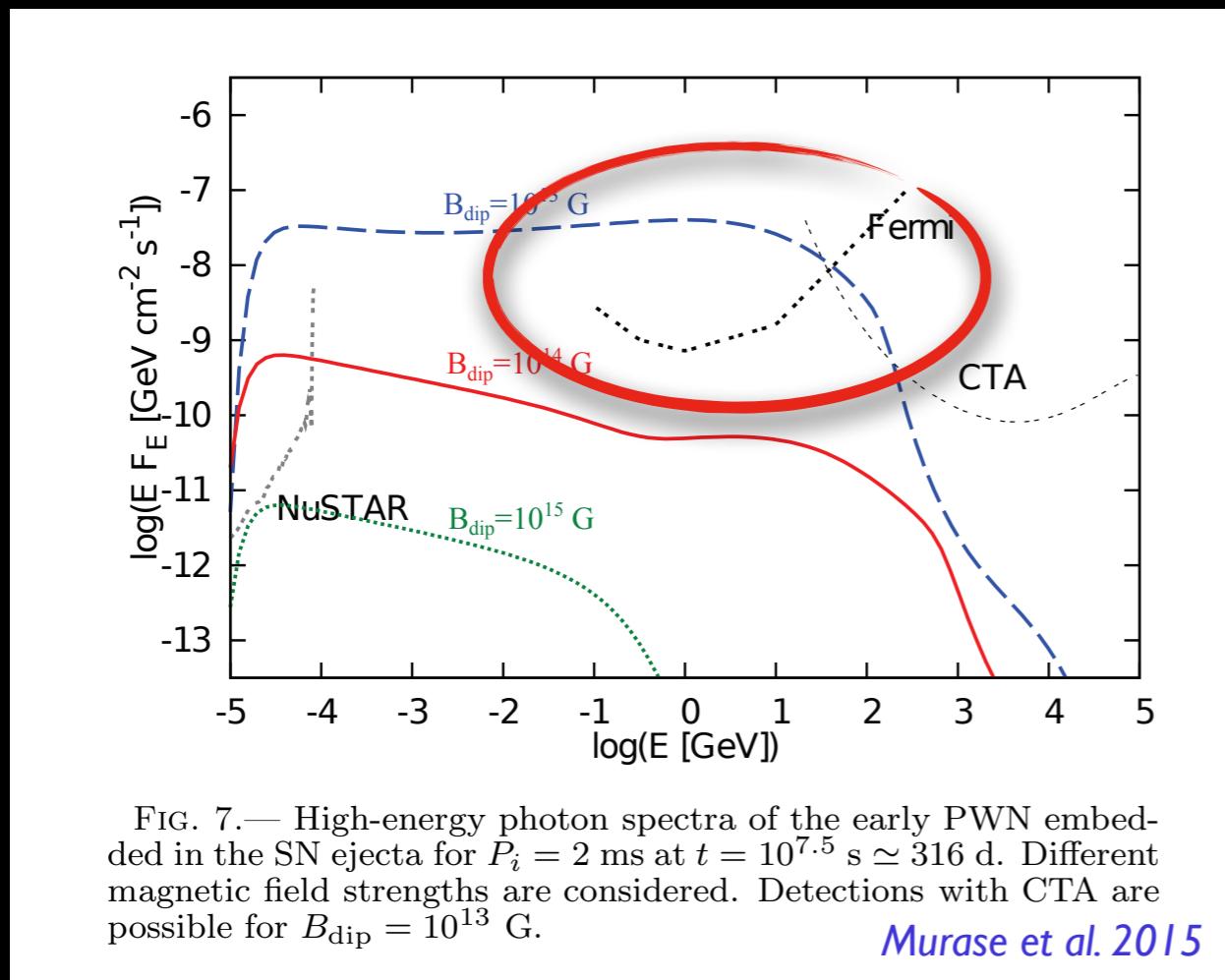


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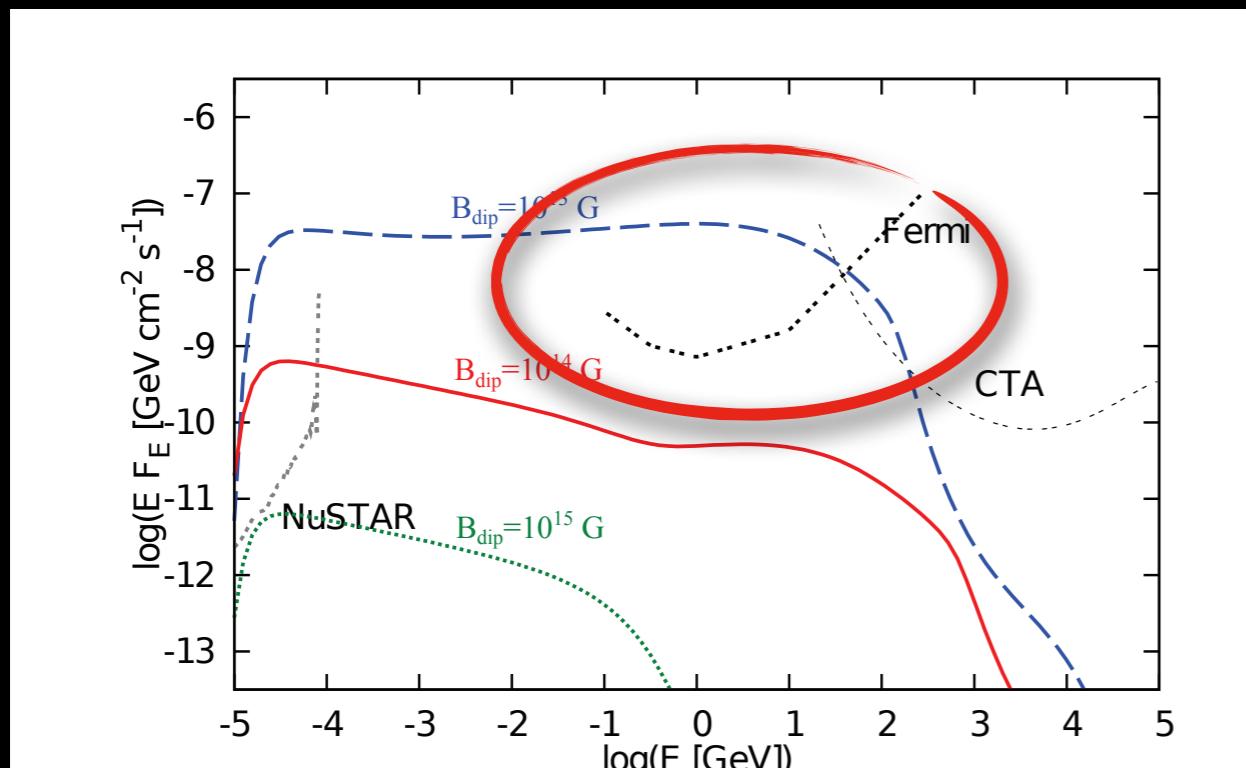
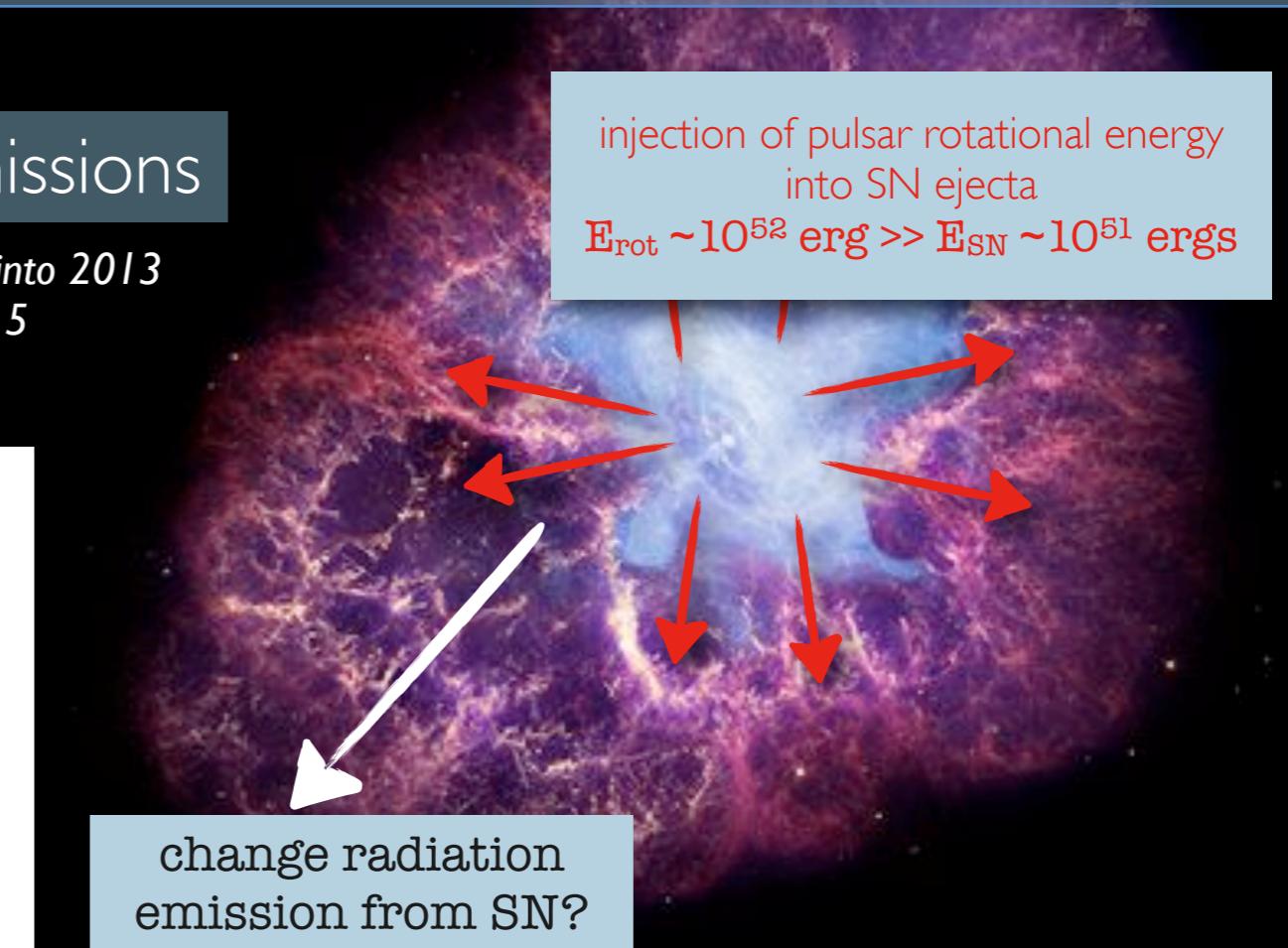
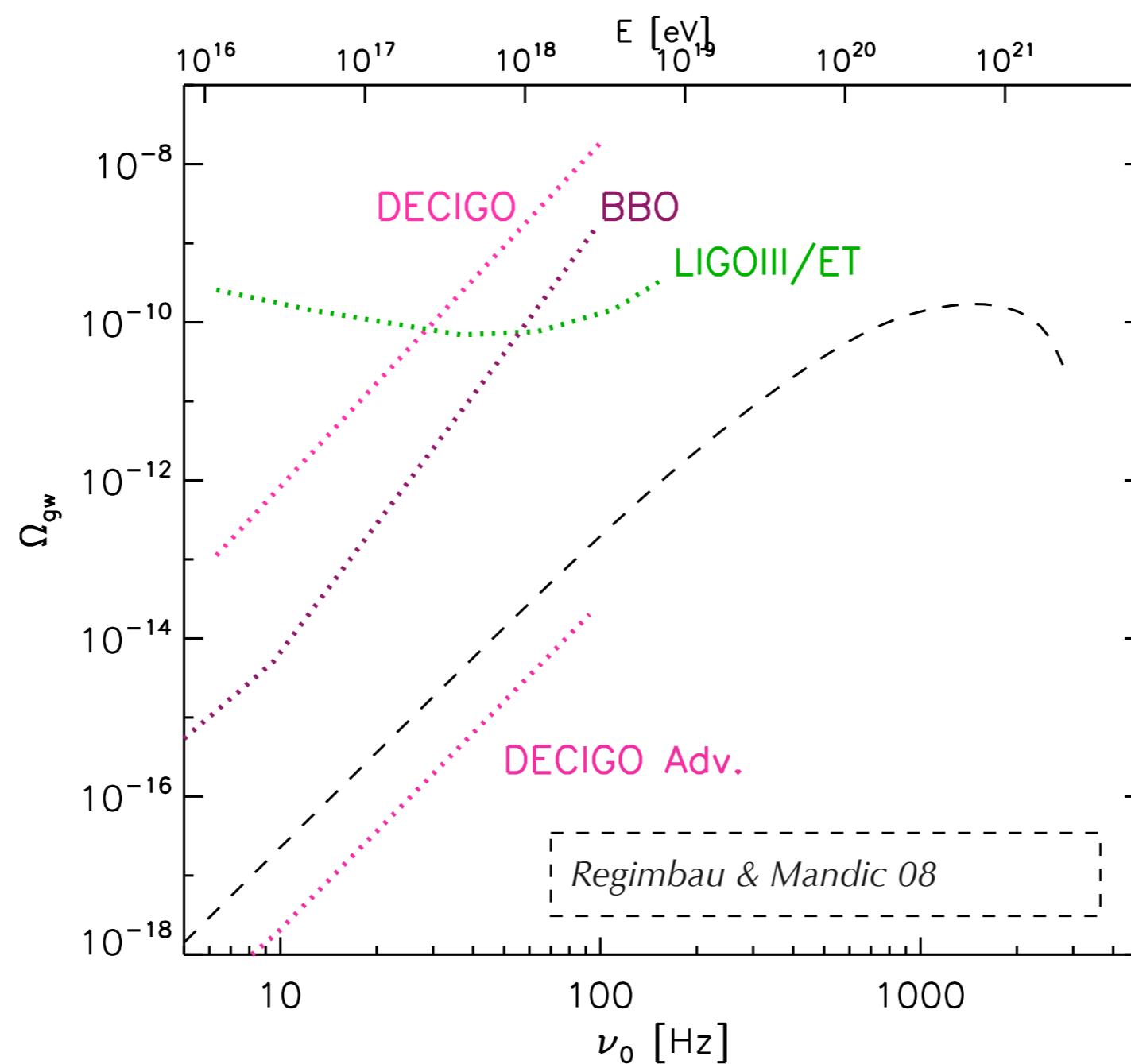


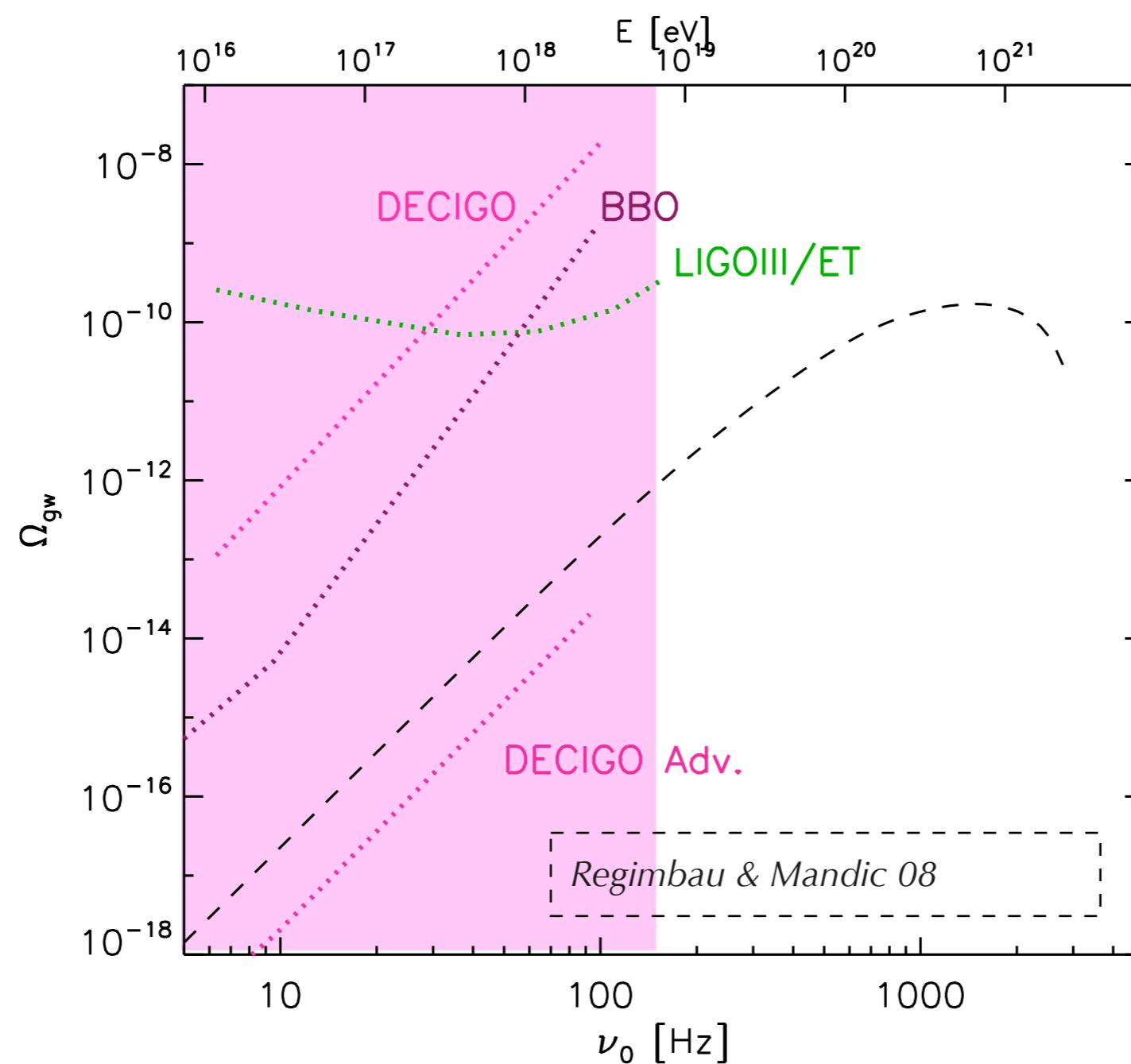
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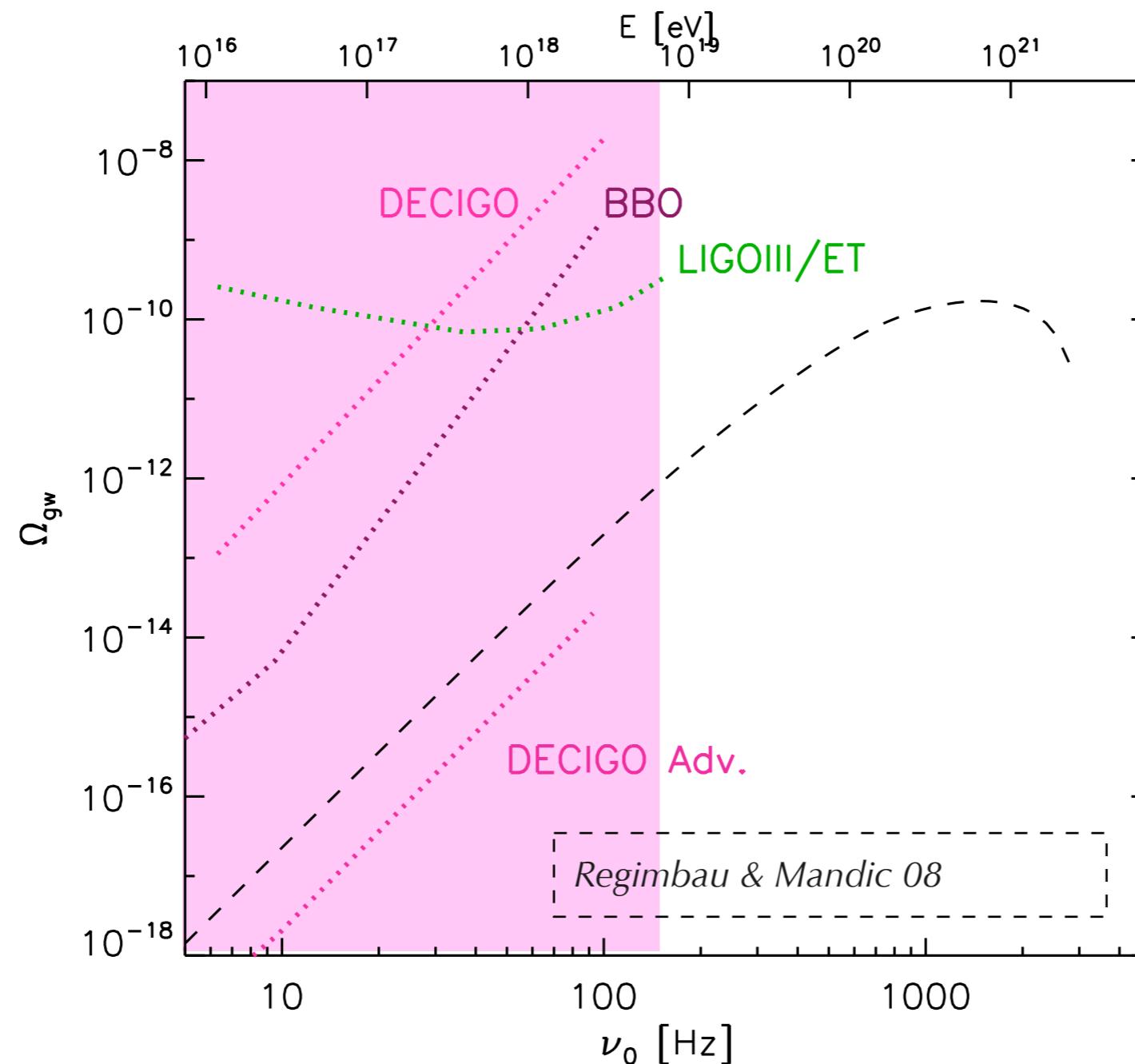
► systematic search with Fermi LAT @ location of SLSNe  
strong constraints on central object *Renault-Tinacci, KK, et al. for the Fermi Coll., in prep.*





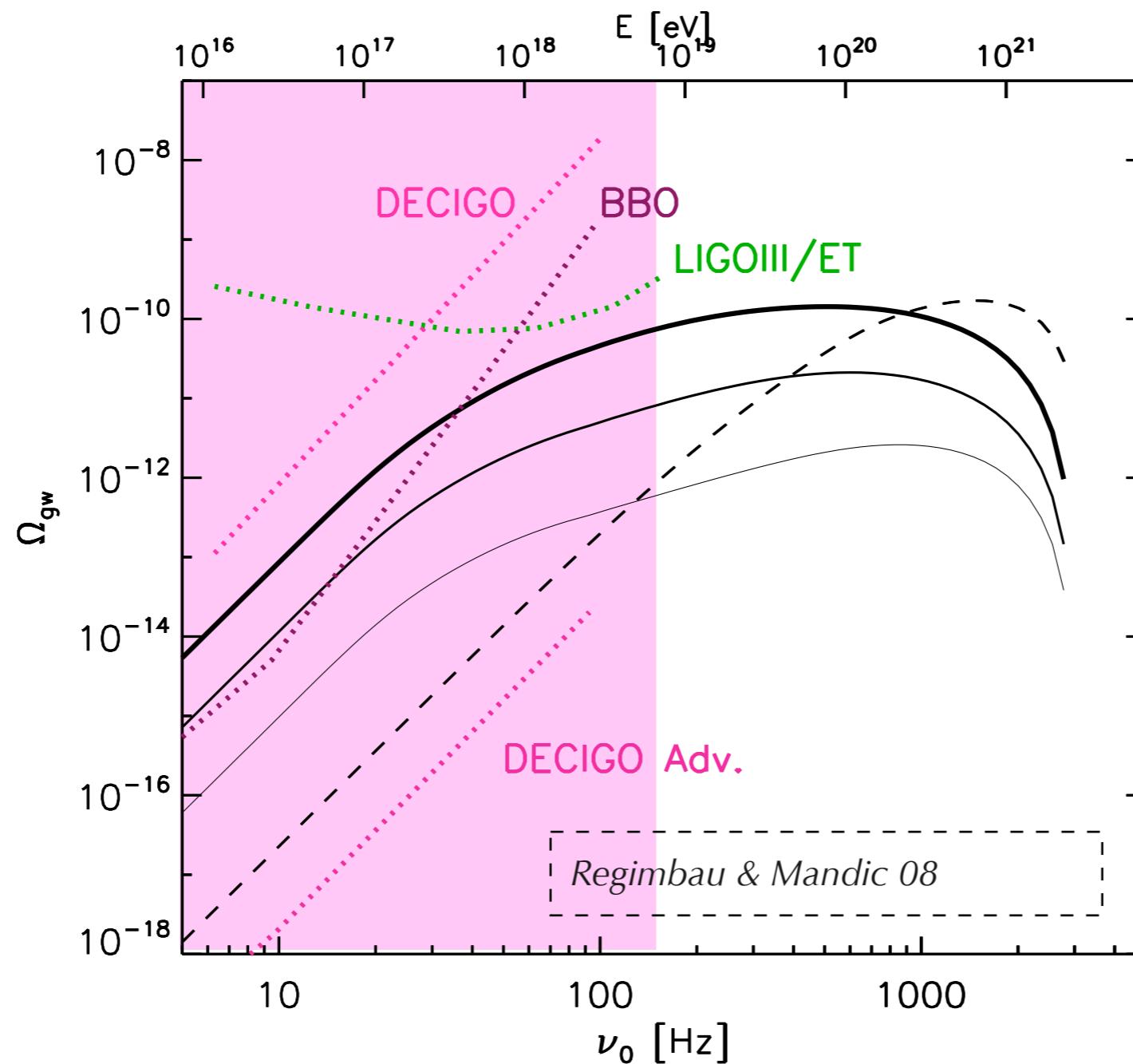
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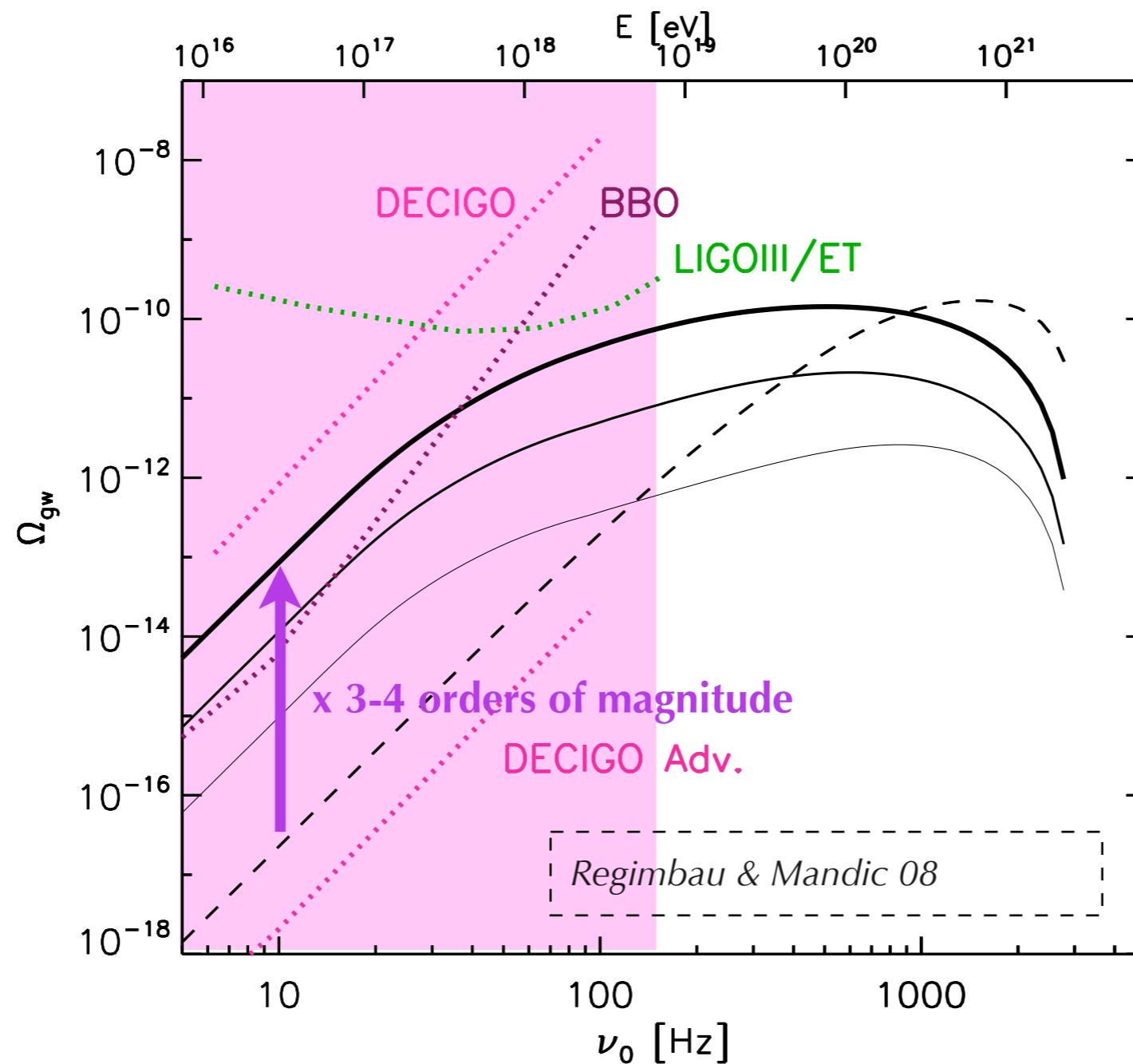
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Why transients are likely sources of UHE messengers

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5-10% of  $E_{\text{CR}}$

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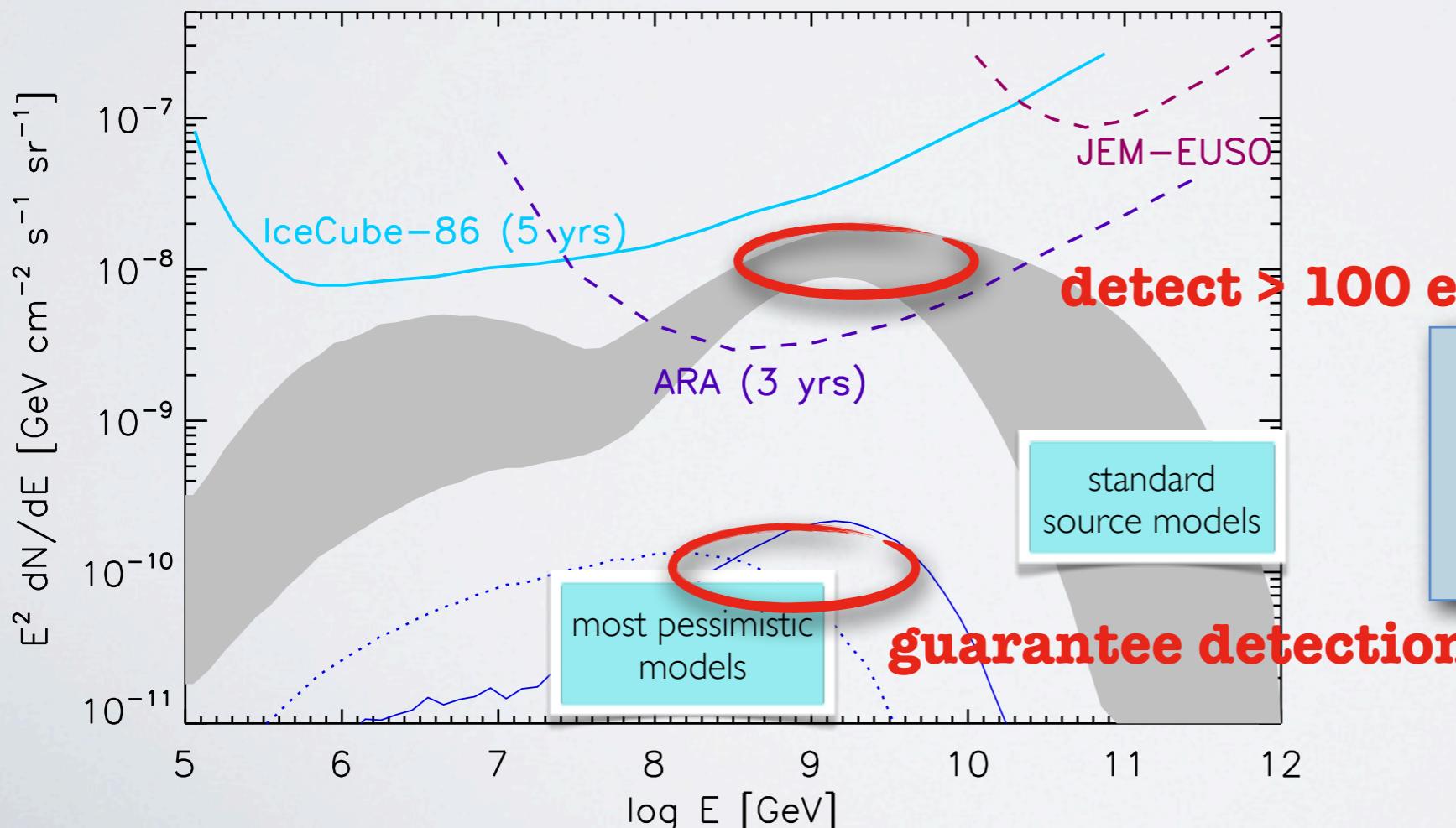
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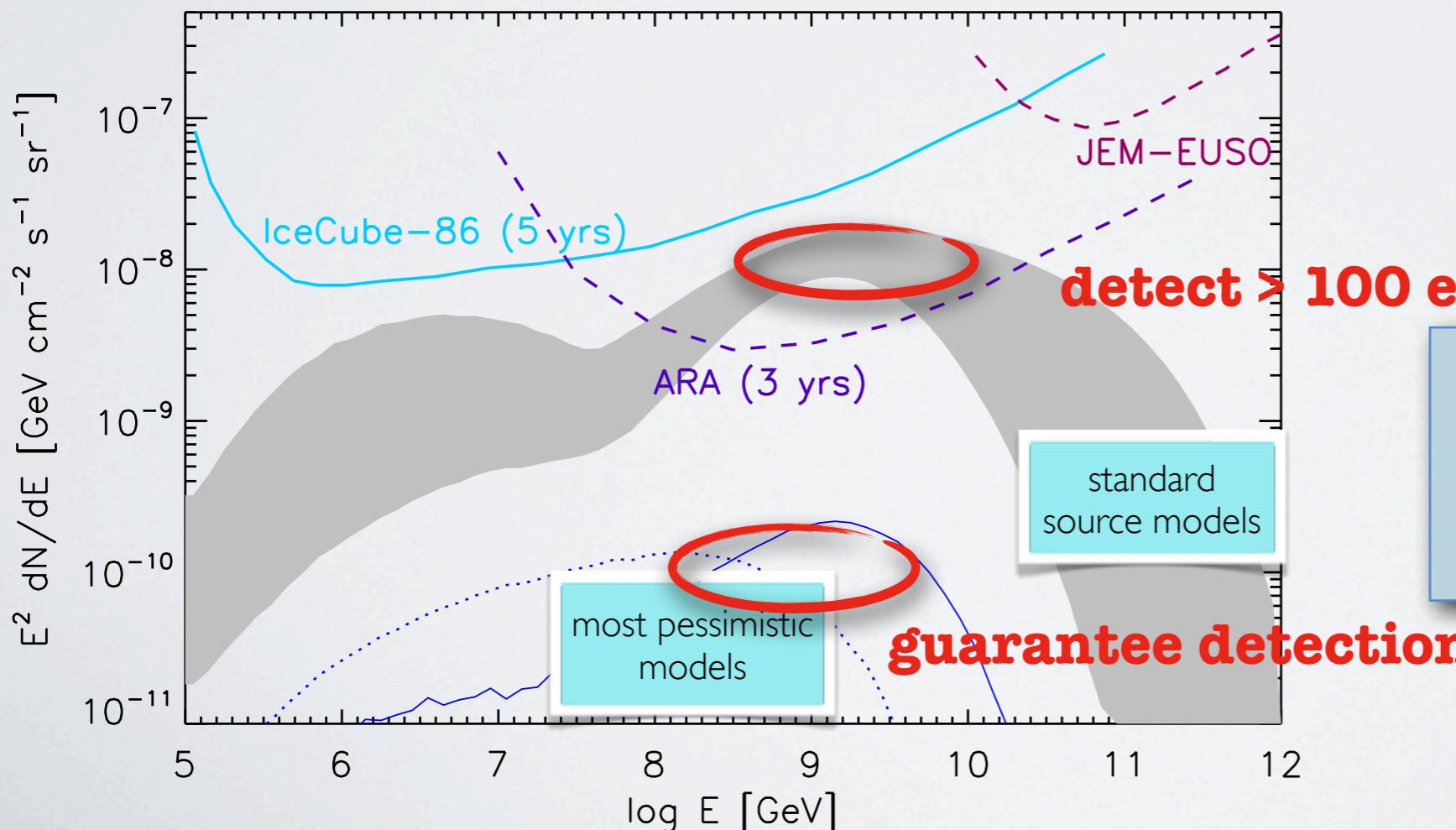
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cosmic rays

## Let's be ambitious

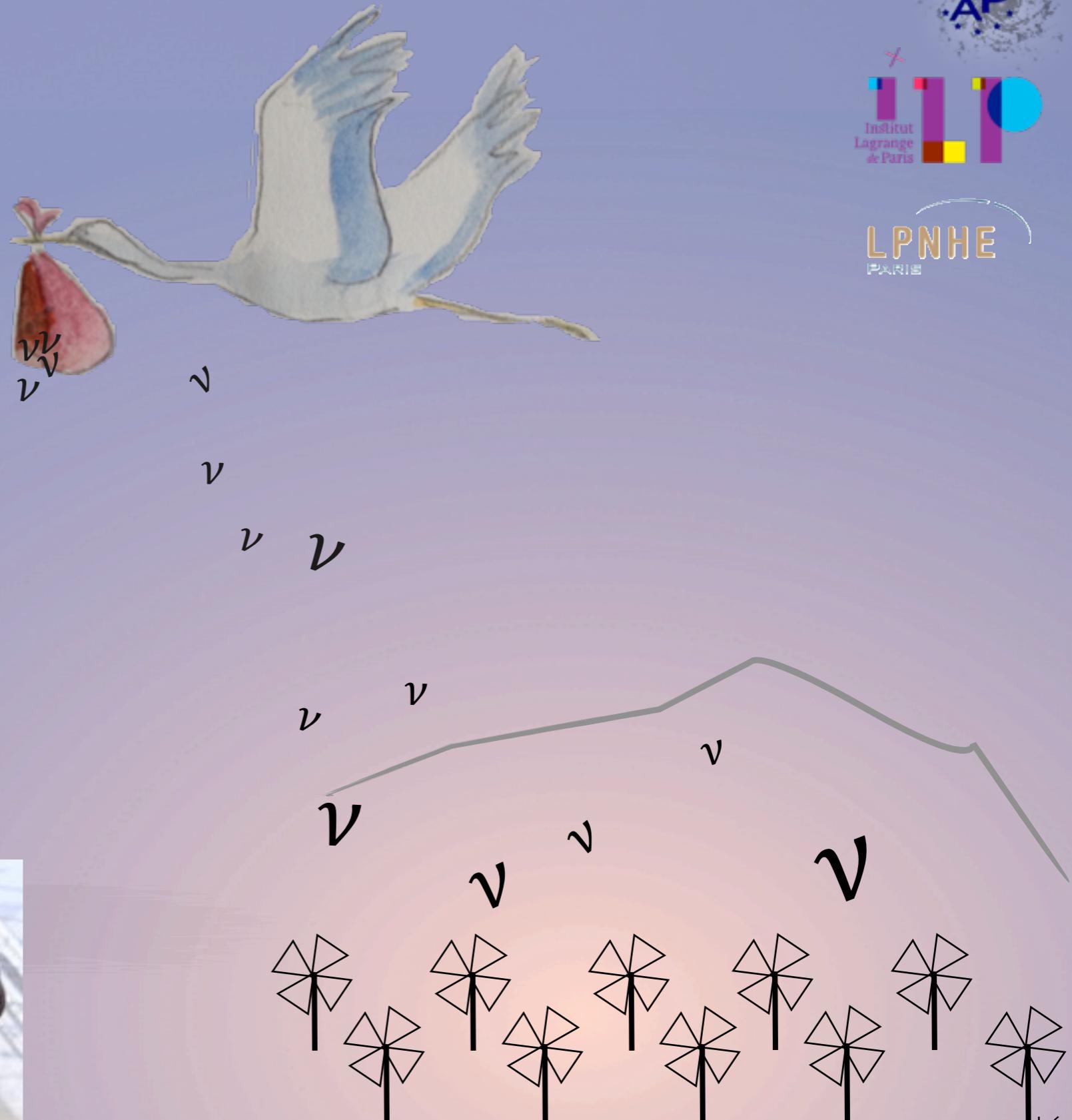


**Cosmogenic neutrinos**  
neutrinos produced when  
UHECRs interact with the cosmic  
photon backgrounds

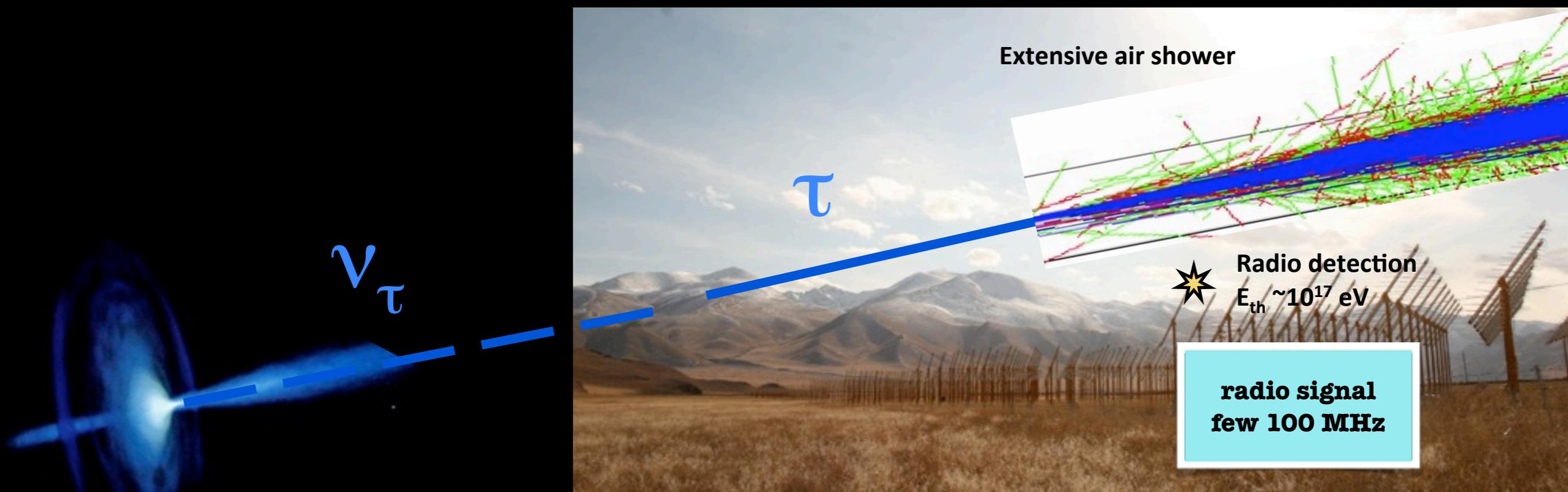


# Proposal for a **G**iant **R**adio **A**rray for **N**eutrino **D**etection

Olivier Martineau  
(LPNHE Paris)



# GRAND neutrino detection principle



- Earth + mountains as target for neutrino interaction  
**Fargion et al. (2000), Bertou et al. (2001)**
- Radio detection of subsequent Extensive Air Shower (good at large zenith angles) on a HUGE array [  $\text{o}(100'000 \text{ km}^2)$  ]

► ICRC 2015: **arXiv:1508.01919**

Olivier Martineau-Huynh<sup>1</sup>, Kumiko Kotera<sup>2</sup>, Didier Charrier<sup>3</sup>, Sijbrand De Jong<sup>4</sup>, Krijn D. de Vries<sup>5</sup>, Ke Fang<sup>6</sup>, Zhaoyang Feng<sup>7</sup>, Chad Finley<sup>8</sup>, Quanbu Gou<sup>7</sup>, Junhua Gu<sup>9</sup>, Hongbo Hu<sup>7</sup>, Kohta Murase<sup>10</sup>, Valentin Niess<sup>11</sup>, Foteini Oikonomou<sup>10</sup>, Nicolas Renault-Tinacci<sup>9</sup>, Julia Schmid<sup>12</sup>, Charles Timmermans<sup>\*3</sup>, Zhen Wang<sup>7</sup>, Xiangping Wu<sup>9</sup>, Jianli Zhang<sup>9</sup>, Yi Zhang<sup>9</sup>

## France

LPNHE  
IAP  
SUBATECH  
U. Clermont-Ferrand  
SAp CEA-Saclay

## China

NAOC  
IHEP  
USA  
Penn State U.  
U. Maryland

## Sweden

U. Stockholm

## Belgium

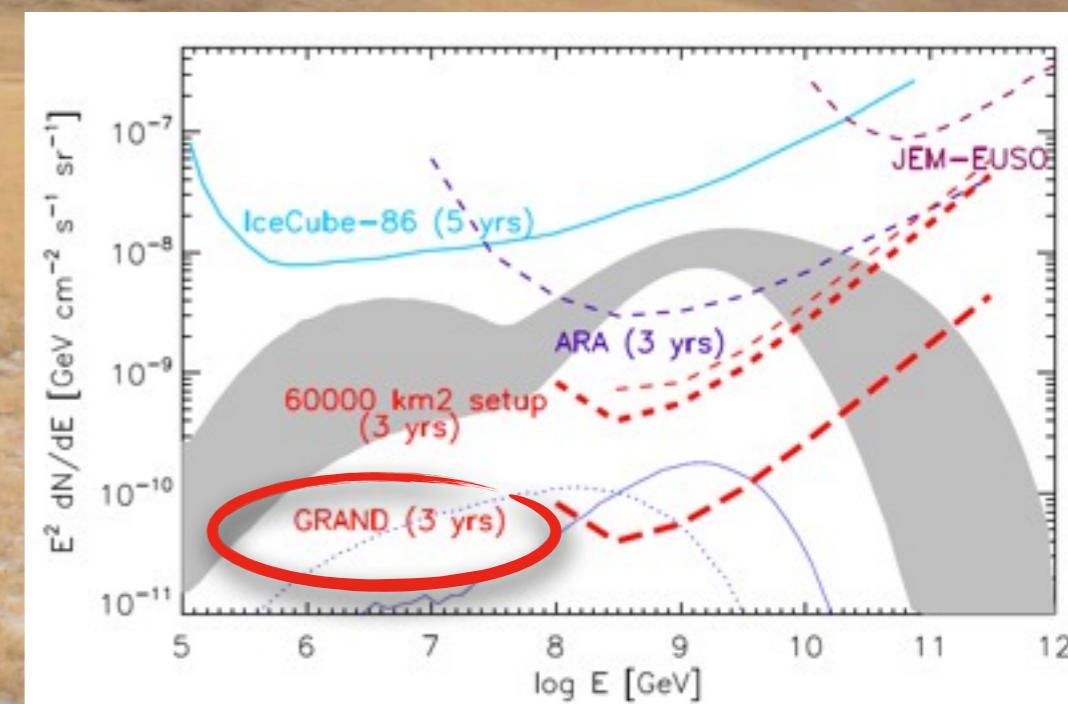
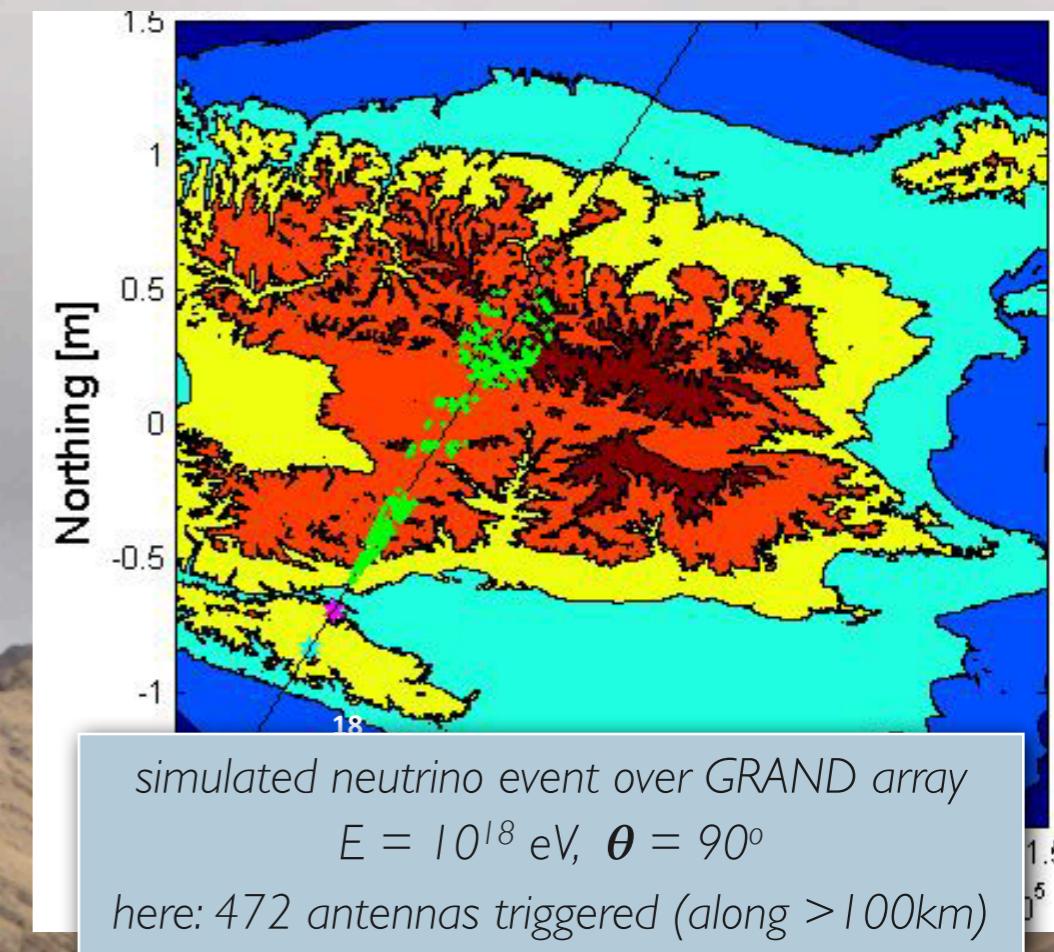
Vrije U. Brussels

## the Netherlands

Nikhef/Radboud U.

# The GRAND project

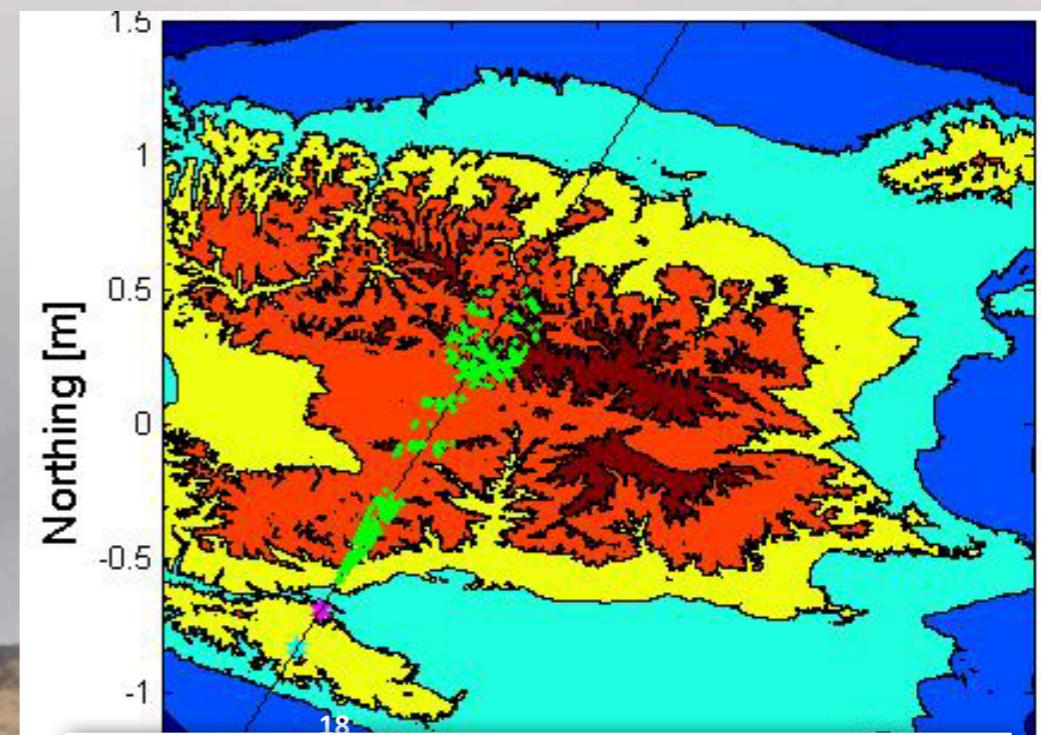
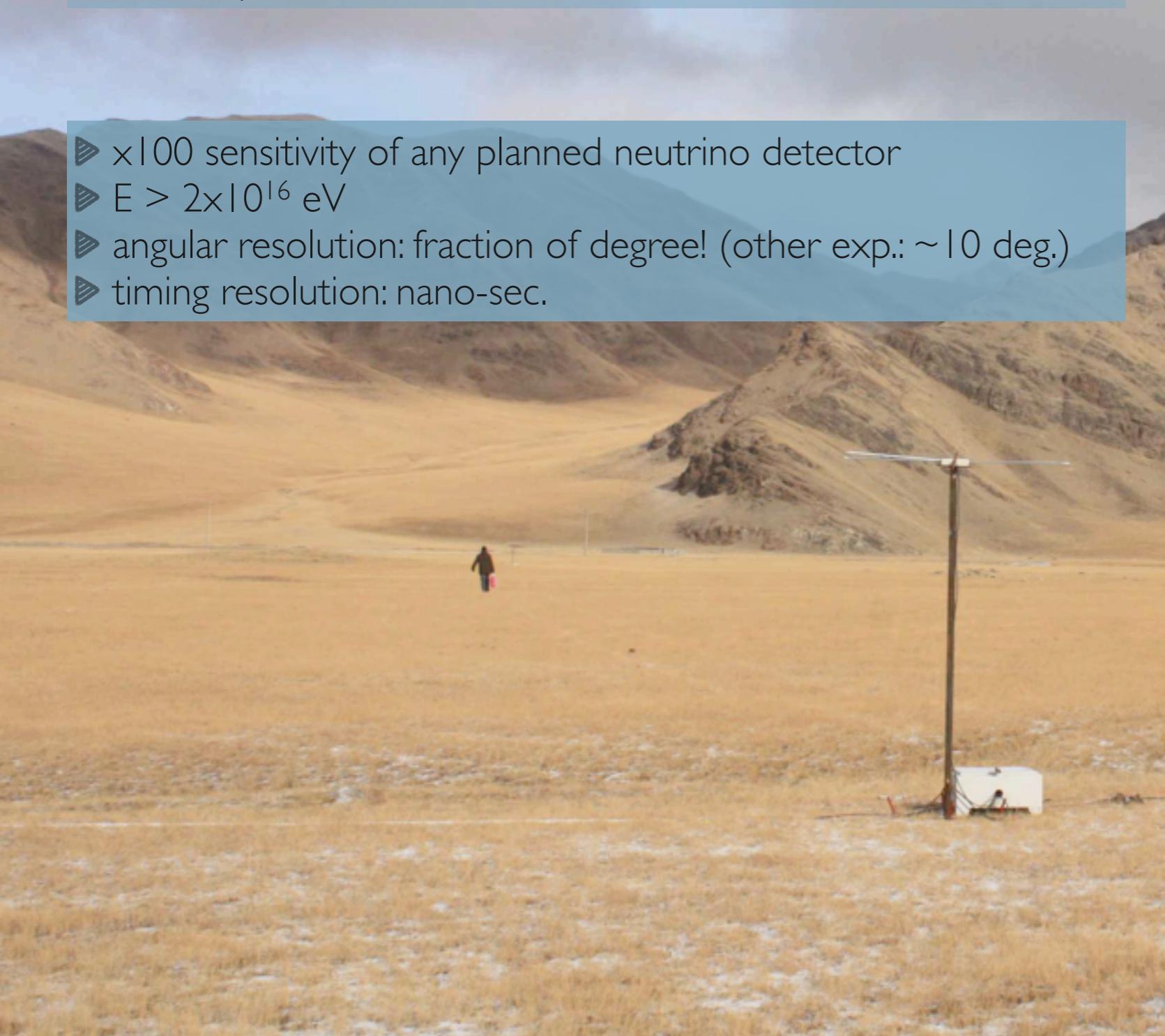
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- ▶ triggering technique tested with TREND in China (Tianshan mountains)



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- ▶  $\times 100$  sensitivity of any planned neutrino detector
- ▶  $E > 2 \times 10^{16}$  eV
- ▶ angular resolution: fraction of degree! (other exp.:  $\sim 10$  deg.)
- ▶ timing resolution: nano-sec.

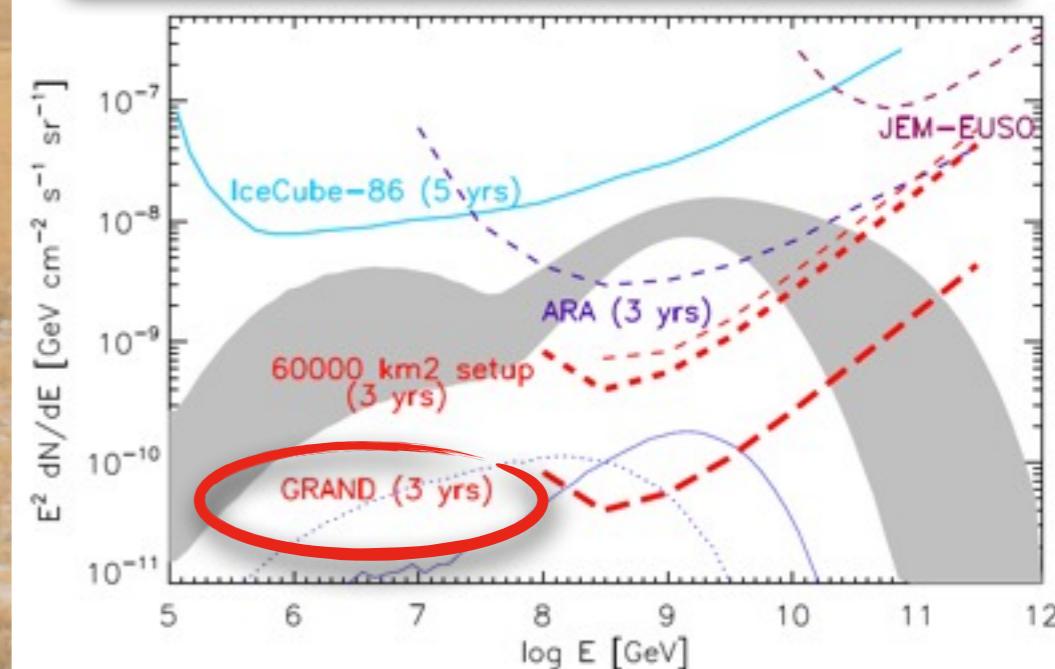


simulated neutrino event over GRAND array

$$E = 10^{18} \text{ eV}, \theta = 90^\circ$$

here: 472 antennas triggered (along  $> 100\text{km}$ )

GRAND sensitivity for all-flavor neutrino flux



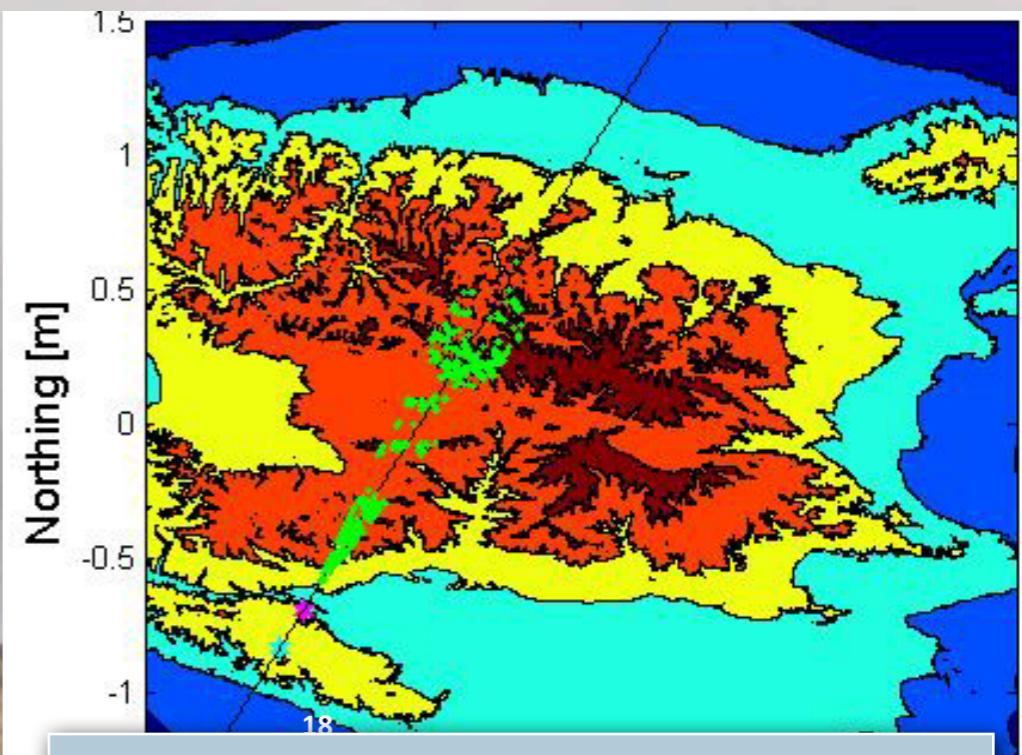
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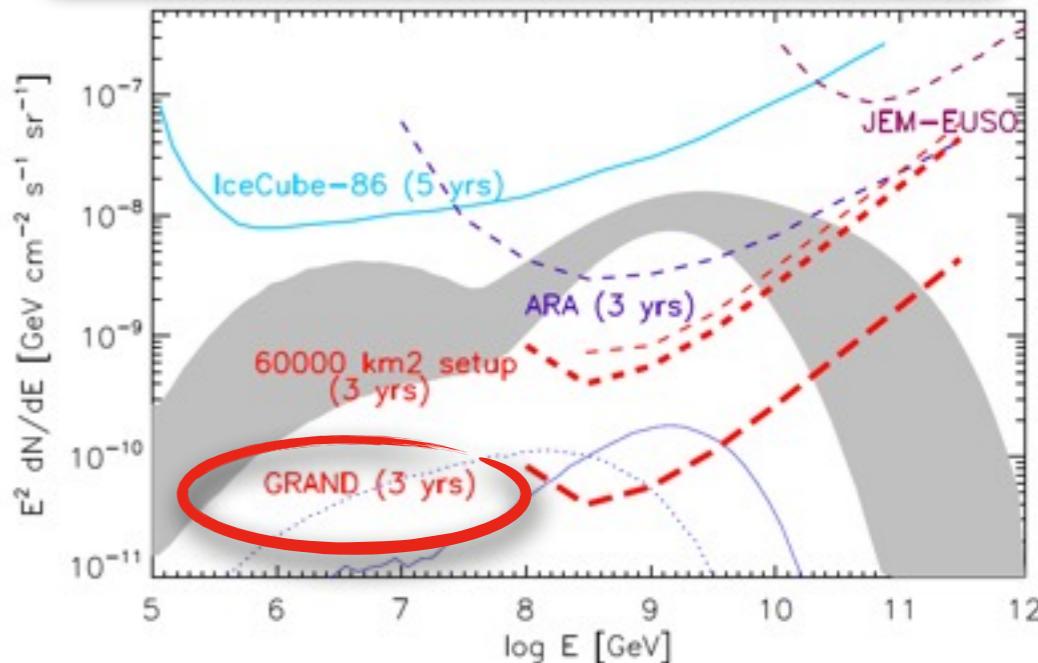
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## Challenges:

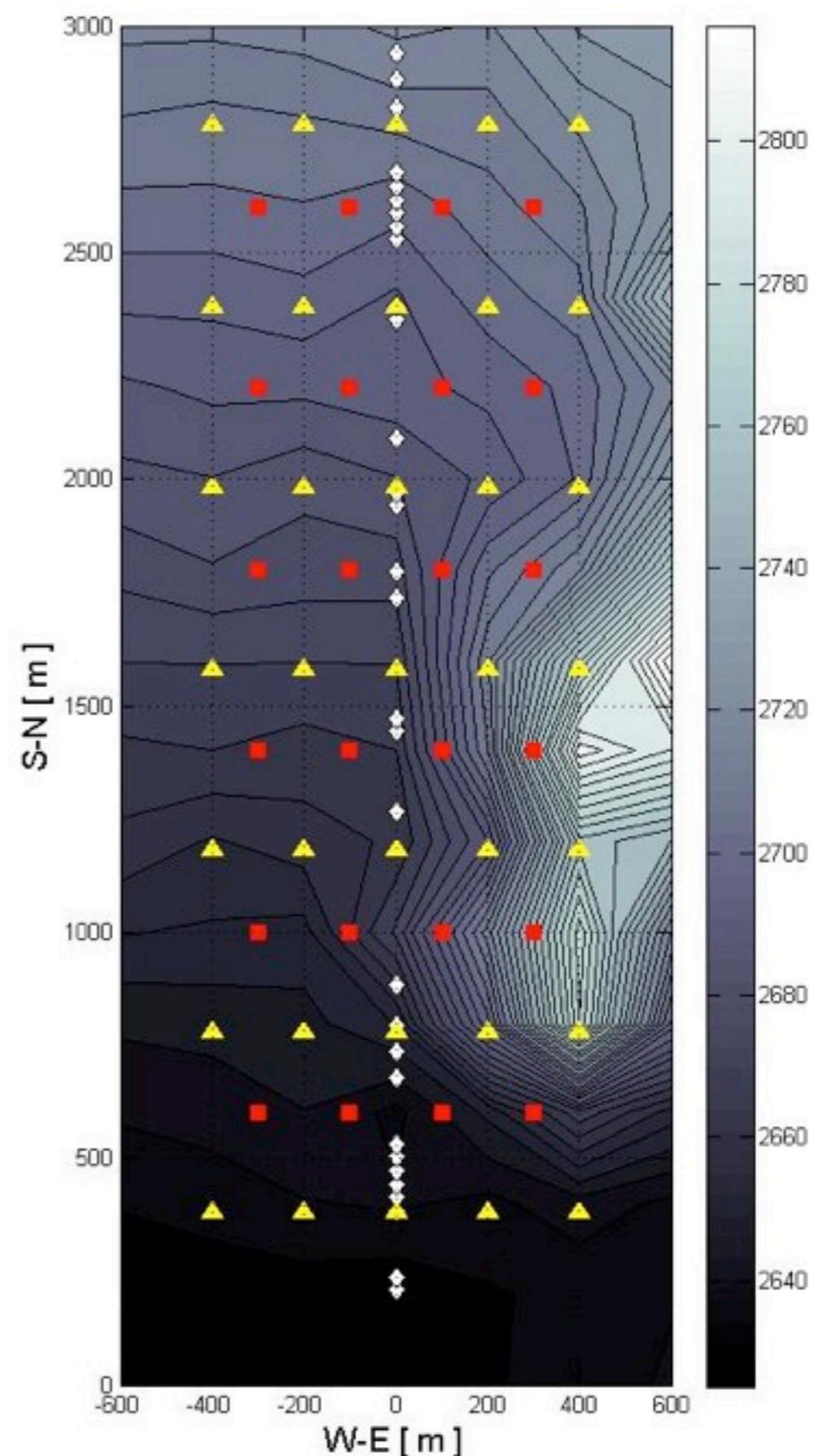
- ▶ poor energy resolution
- ▶ sky coverage
- ▶ technical challenges: background noise rejection (will be tested with 35-antenna prototype), communication of 45k antennas



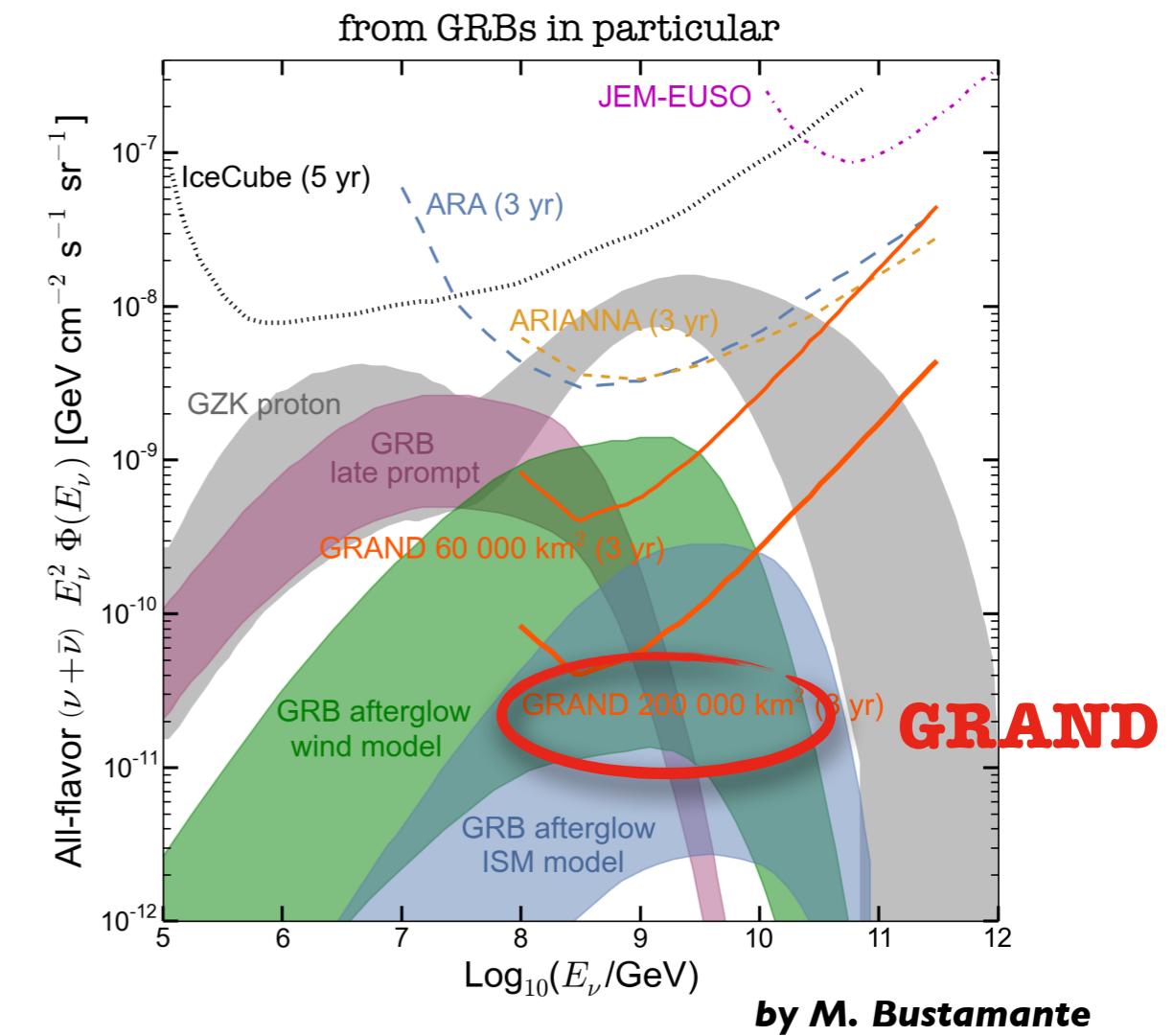
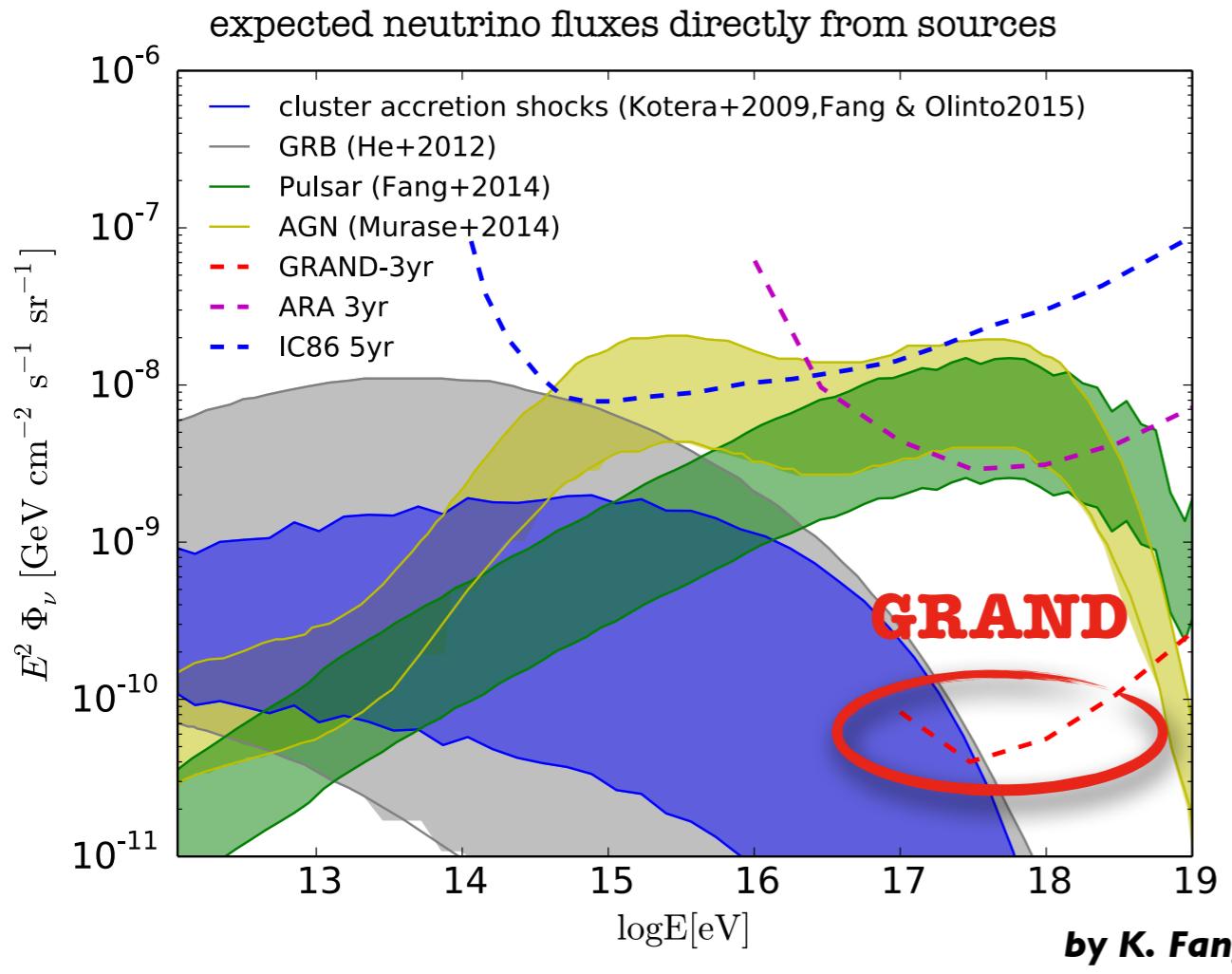
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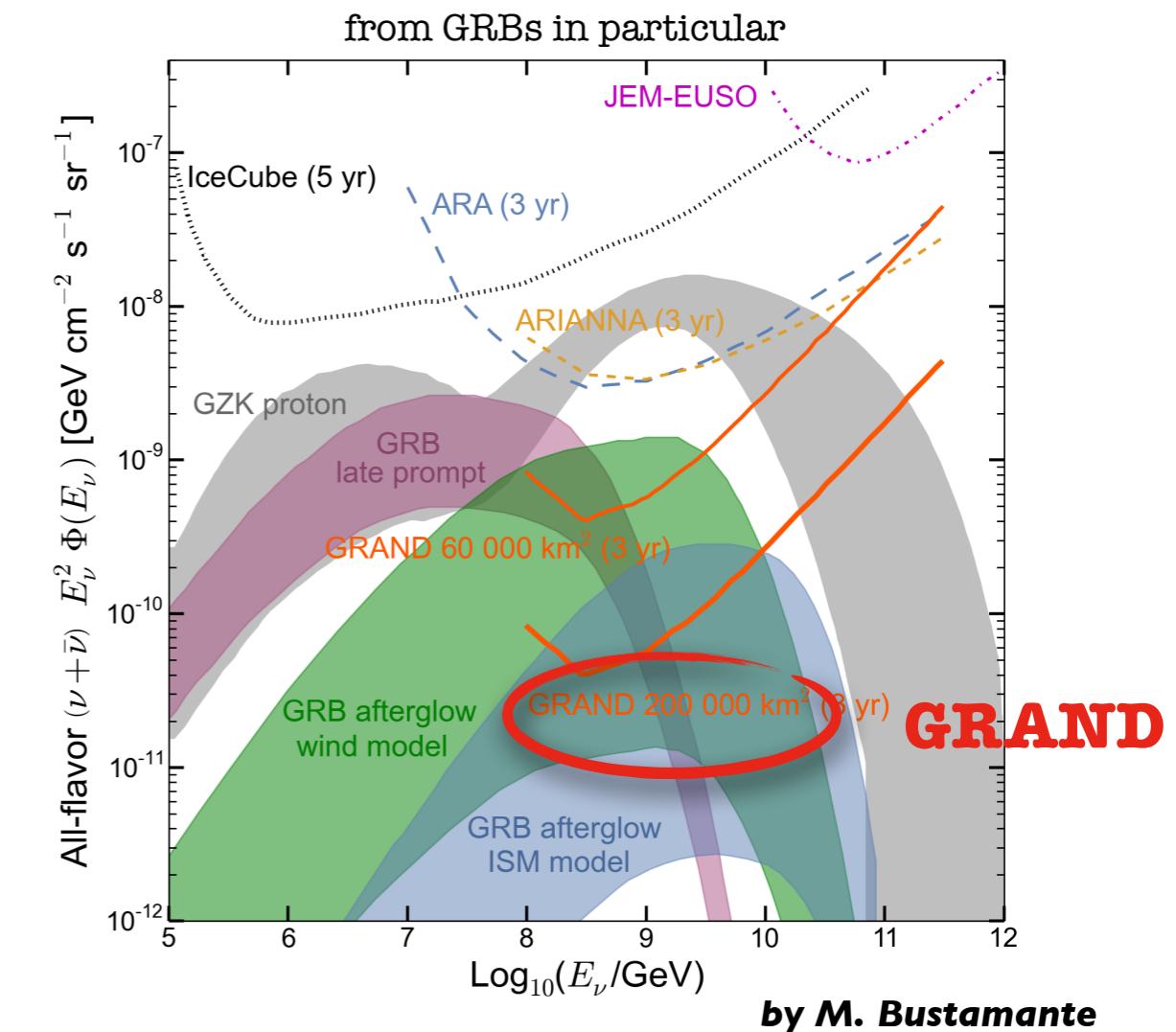
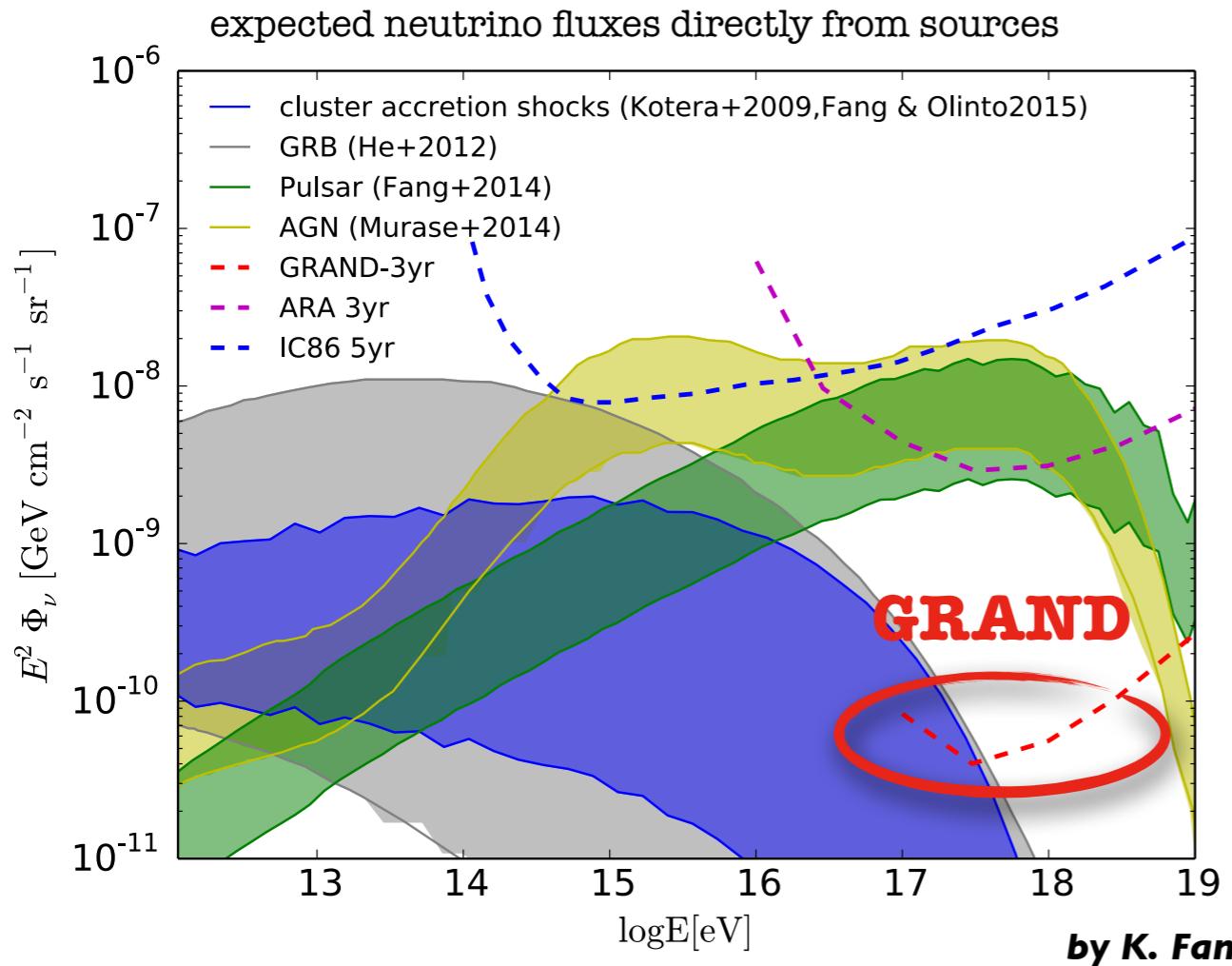
- ▶ Hybrid setup with 35 3-polar antennas + 24 scintillators
- ▶ Target: (standard) air showers coming from North with  $40^\circ < \theta < 70^\circ$
- ▶ Principle: select radio candidates from polar info, use scintillator array as a cross-check  
--> qualitative determination of rejection factor
- ▶ Deployment on-going, to be completed before June 2016
- ▶ Proposal to perform similar tests @ AUGER-AERA



# Neutrino astronomy and other Science Cases with GRAND

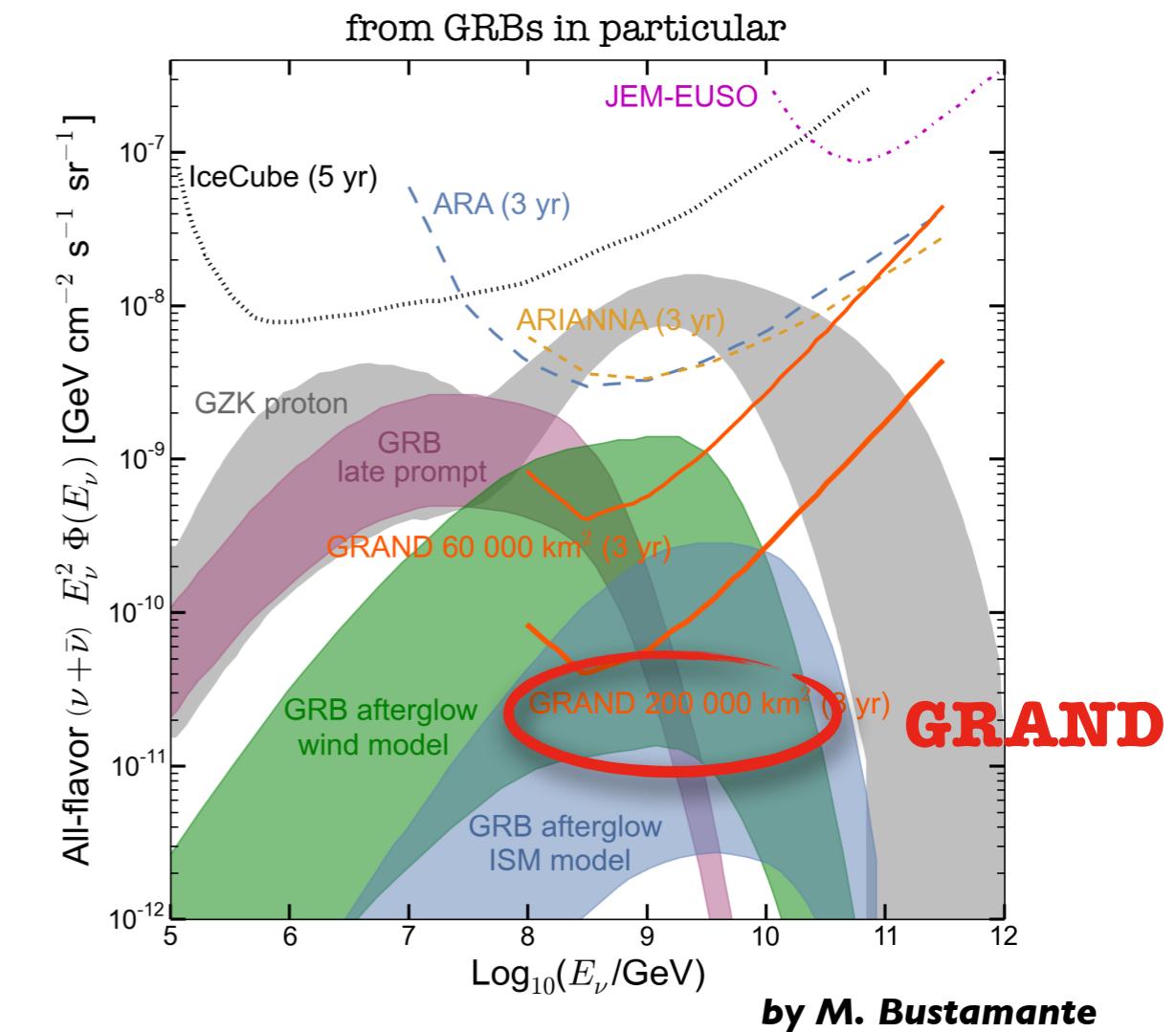
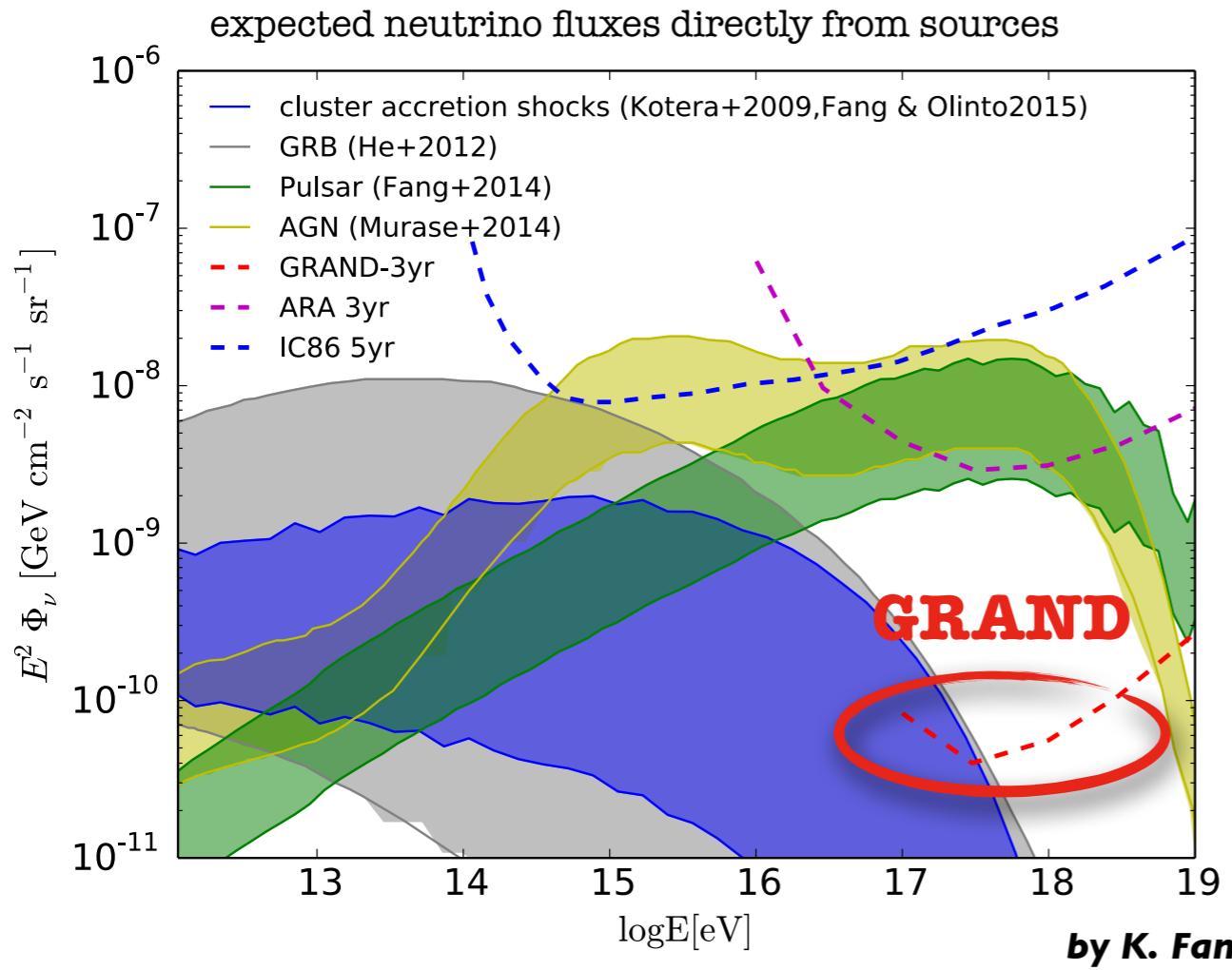


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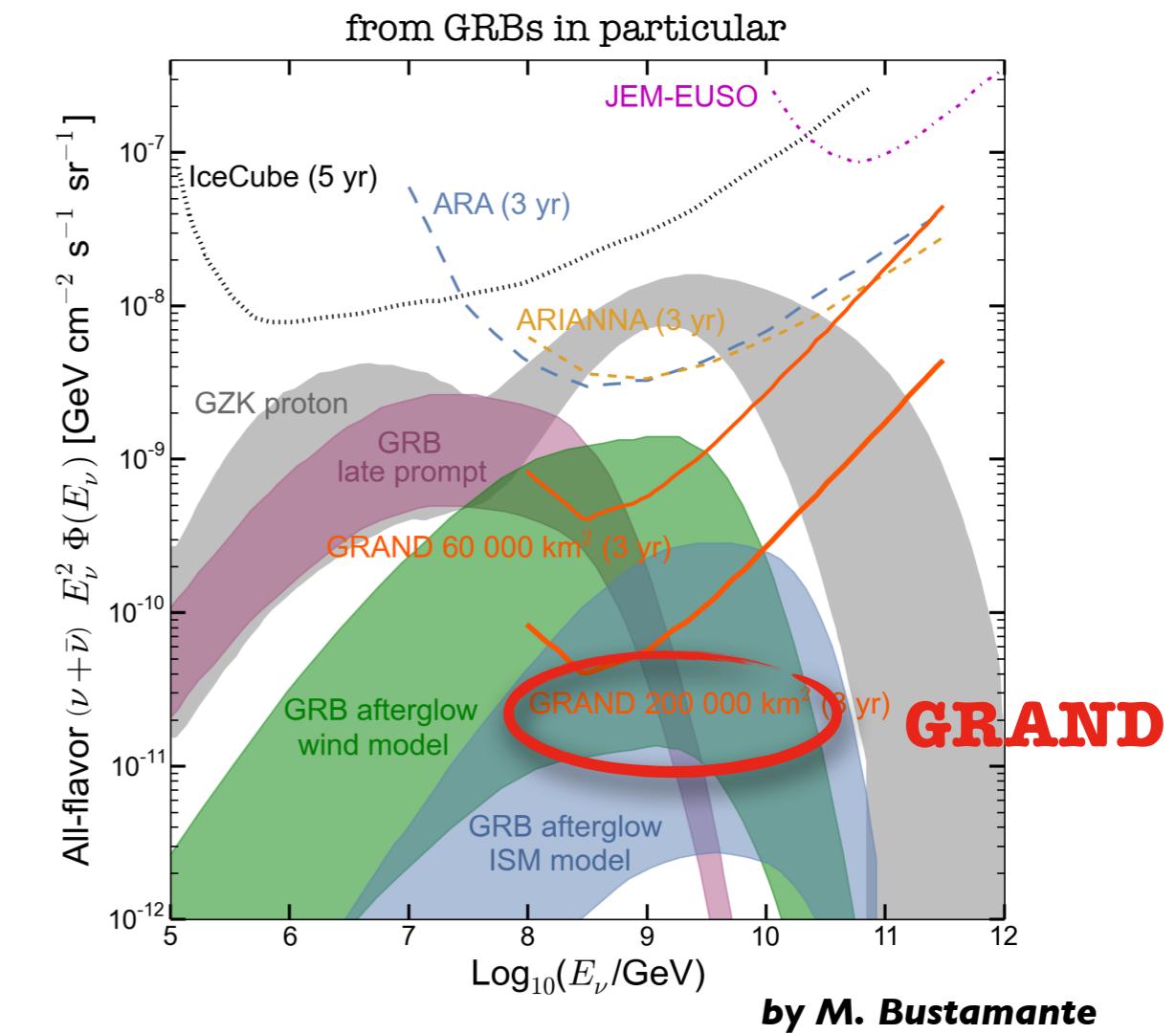
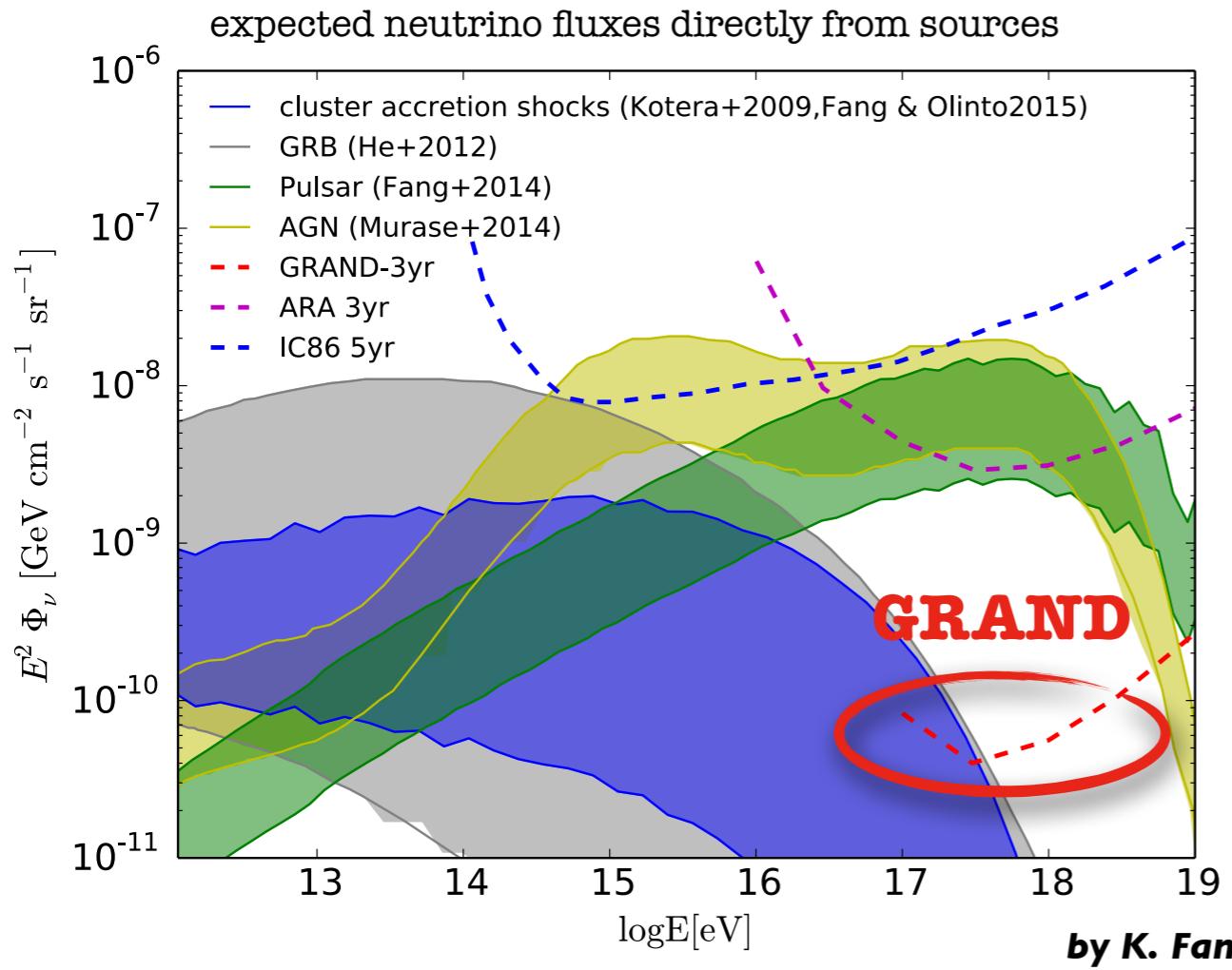
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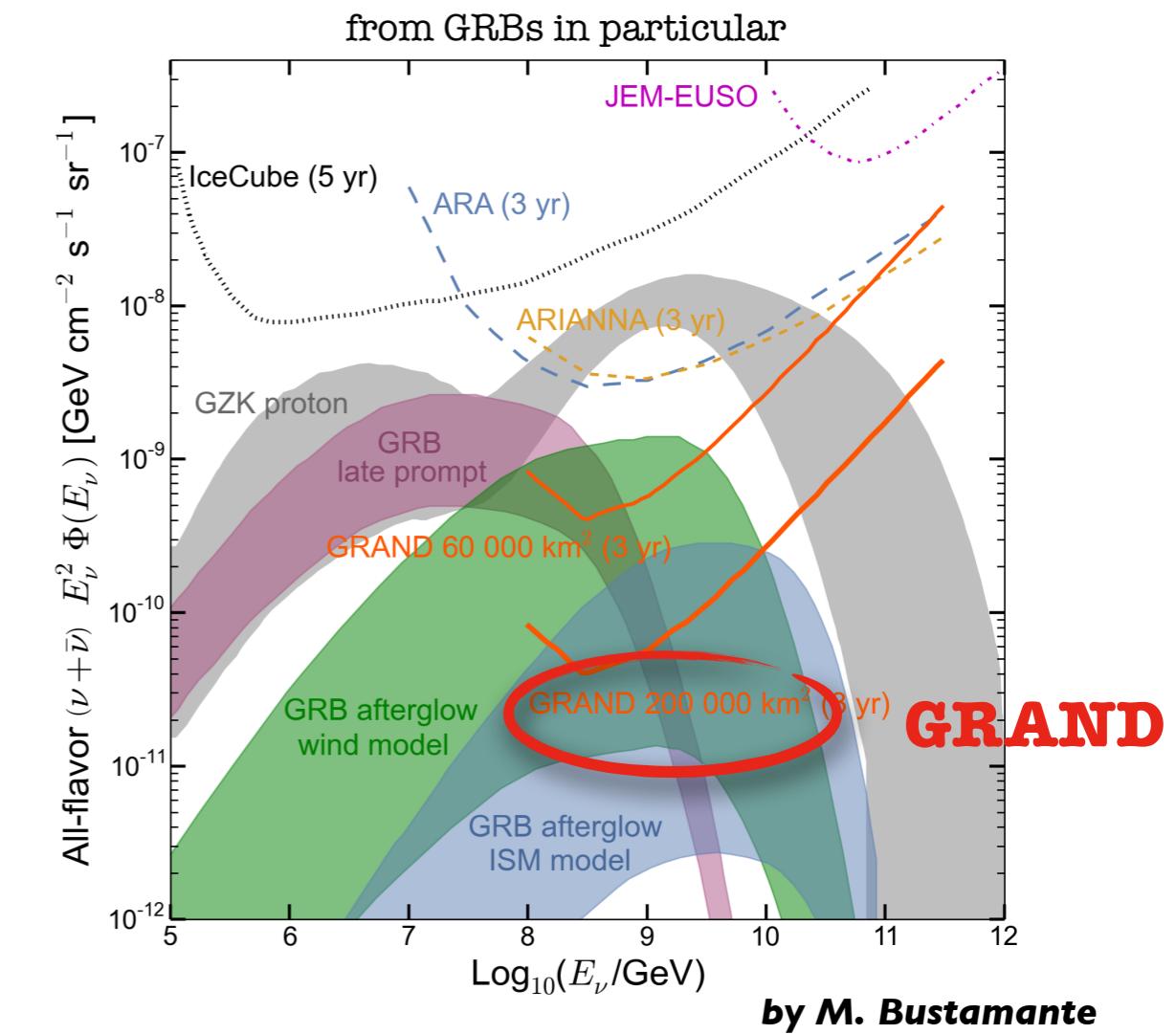
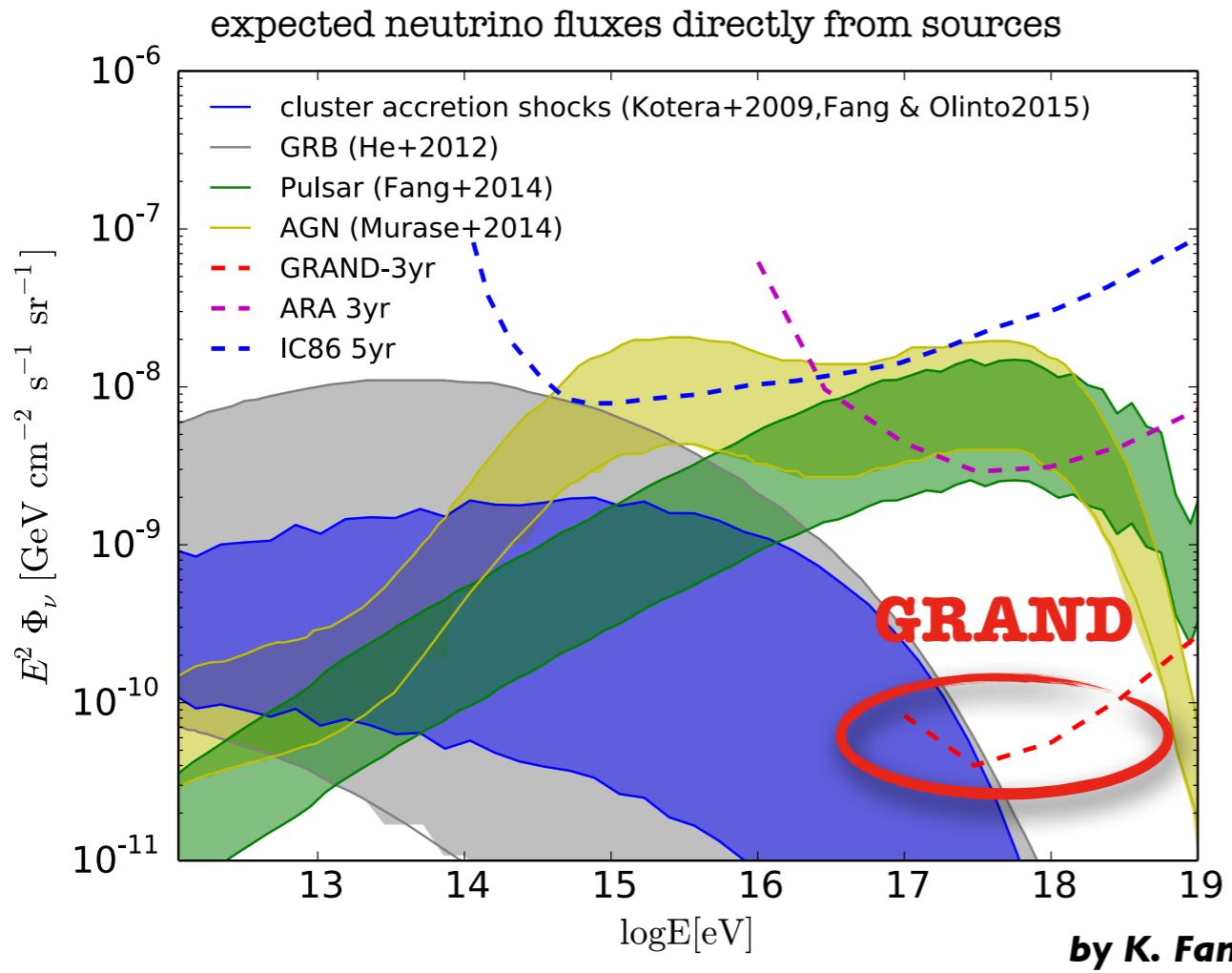
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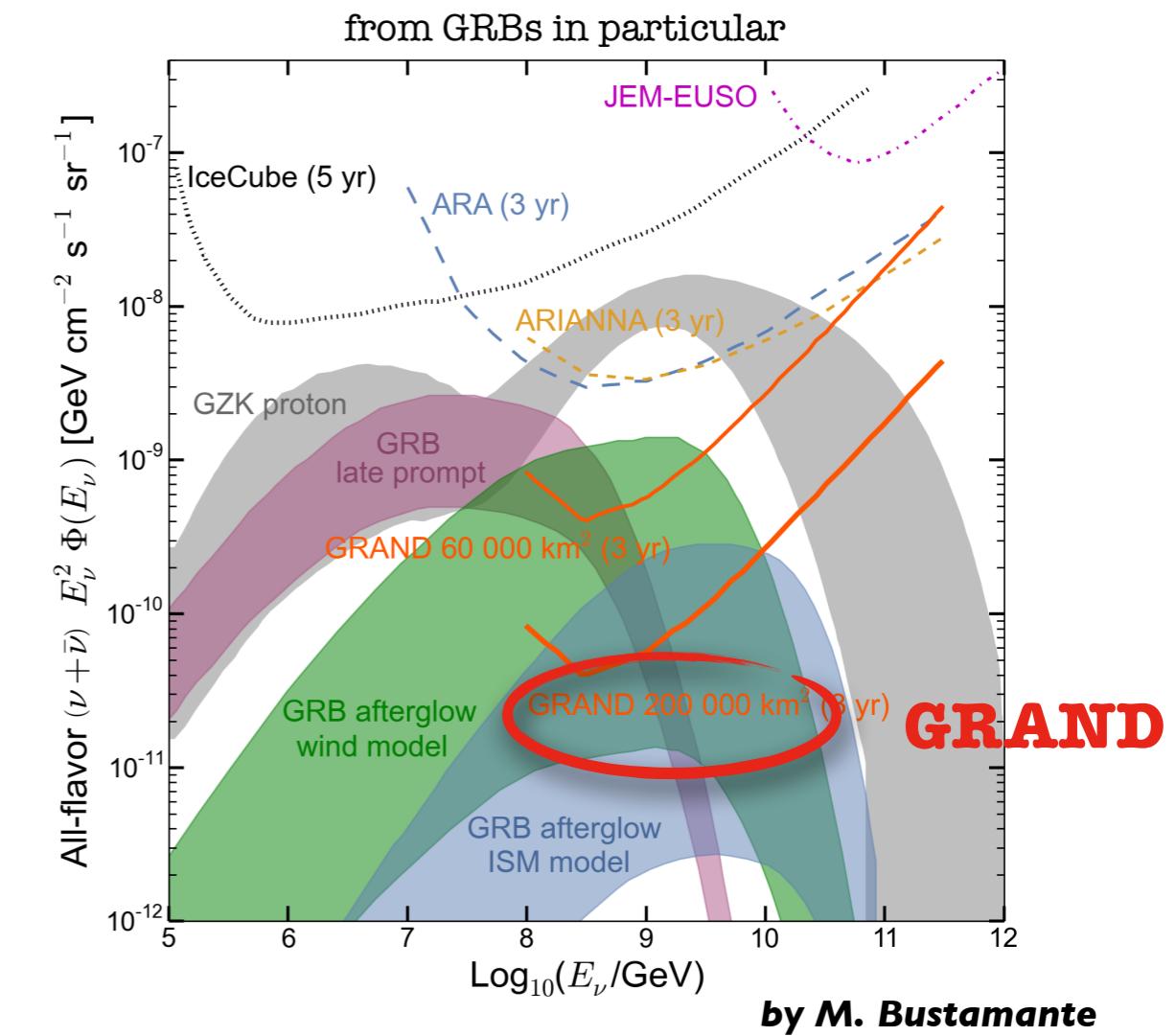
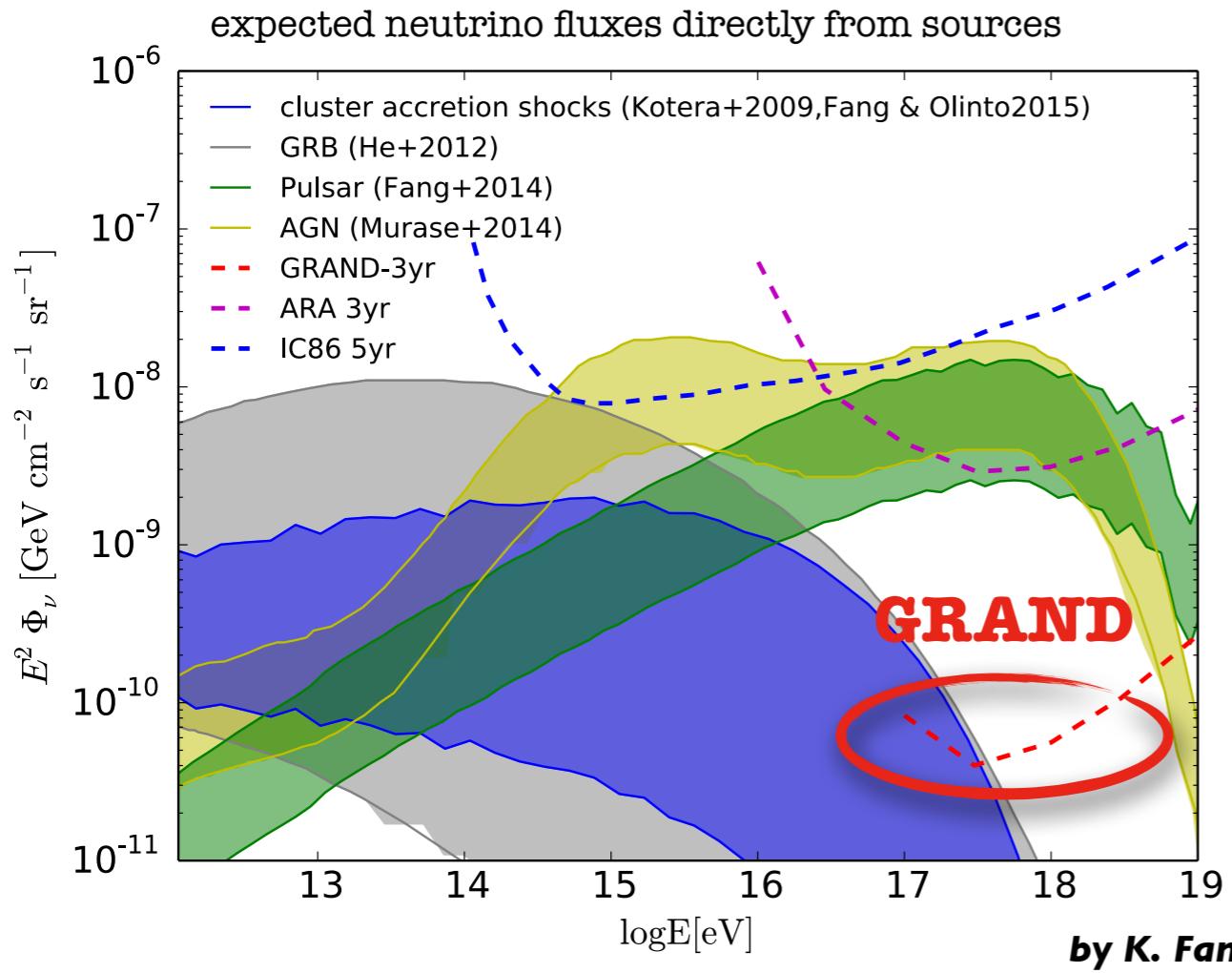
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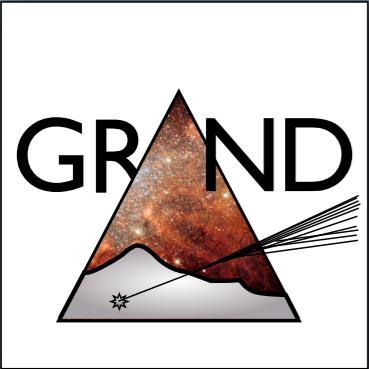
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Science case to be defined in more details!  
Work in progress.



# Perspectives

- ▶ GRAND: a dream tool for multi-messenger astronomy at VHE
- ▶ GRAND proposal being set-up (science case +  $\nu$  sensitivity)
- ▶ Possible timeline:
  - ▶ 2016: proposal
  - ▶ 2018: engineering array (  $\approx 1000 \text{ km}^2$  )
  - ▶ 2021: GRAND deployment
- ▶ Join us! ☺

